THE BOOK WAS DRENCHED

A COMPREHENSIVE TREATISE ON
ENGINEERING GEOLOGY

PHOTOGRAPH I.

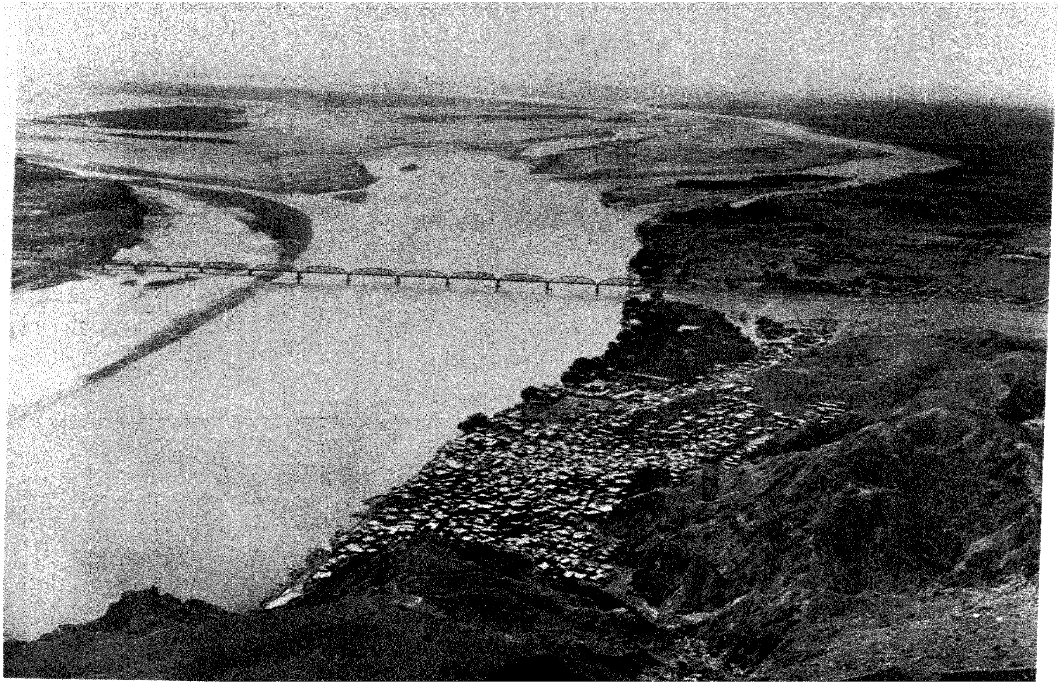
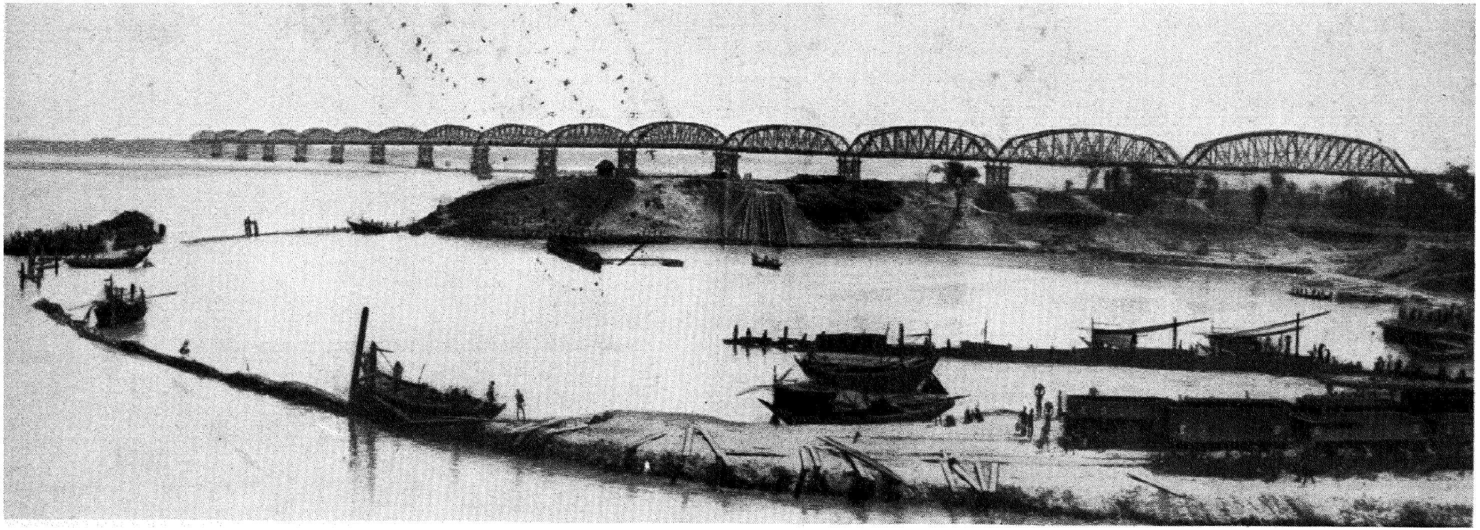


Photo by E. R. *Gee.*] [D.G.S.I.

THE DEBOUCH OF A RIVER.

The Indus is seen leaving the Punjab hills at Kalabagh. The deposition of silt in a deltaic fan is due to the reduced velocity of the current. The location of the bridge has been cleverly chosen.

PHOTOGRAPH II.



Per favour "The Statesman," Calcutta.] RIVER CONTROL OPERATIONS. [*Photo by "The Statesman," Calcutta.*

Protective work in progress to keep the river to its channel under the bridge. The action of the current has been to change the course of the river south of the bridge and thus outflank it.

THE HARDINGE BRIDGE OVER THE RIVER GANGES, BENGAL (1934).

A COMPREHENSIVE TREATISE
ON
ENGINEERING GEOLOGY

By

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TO

MY WIFE

AUTHOR'S NOTE

Nearly 15 years ago, while together on a survey in British Garhwal, Major, now Colonel E. P. Anderson, D.S.O., R.E., suggested that an outline of the geological principles relating to engineering questions would be useful to civil engineers. With this in mind I chose " Some Engineering Aspects of Geology " as the subject for a lecture which Sir Edwin Pascoe asked me to give in the Indian Museum, Calcutta. Later, in 1921, through the kindness of Sir Thomas Holland, I elaborated that lecture and presented a paper to the then newly formed Institution of Engineers (India). And in 1923, with the generous consent of their council, I was able to publish an outline of the subject in book form as " Civil Engineering Geology." It was criticised by my friend Mr. D. N. Wadia as " tantalisingly brief." It is now practically *out of print*. However, I have felt that a larger work has been overdue for some years. I have slowly compiled information from various sources, and, with my own experiences during the past 10 years, put together the whole in this new book " Engineering Geology." It is to take the place of the older book and I trust it may prove of use to all those who may turn to it for information.

As will be seen many of the photographs are from the official collection of the Geological Survey of India. Some had previously been used as illustrations in " Civil Engineering Geology " and the others have been largely obtained through the kindness of Dr. L. Leigh Fermor, F.R.S., Director, Geological Survey of India (D.G.S.I.). I am also indebted to other colleagues—Messrs. H. Crookshank, D. N. Wadia, G. V. Hobson, E. R. Gee, W. D. West, J. B. Auden and Drs. A. M. Heron and J. Dunn for photographs or data or criticism in connexion with this new book. I am under an obligation to many friends overseas—in New Zealand, South Africa and England, including the late Dr. J. W. Gregory—who have most kindly sent me copies of published papers relating to the subject of Engineering Geology. Miss C. M. Macmillan and my wife have spent many hours reading over my manuscript or assisting in other ways. My wife has typed the entire script. Without her help the book could not have been prepared for publication just now.

C. S. F.

Geological Survey Office,
Calcutta.

TABLE OF CONTENTS

PART II—FIELD OPERATIONS

PART III—WATER SUPPLY

ILLUSTRATIONS

PHOTOGRAPHS

TEXT FIGURES

PHOTO-MICROGRAPHS

PART I

BUILDING MATERIALS

ENGINEERING GEOLOGY

CHAPTER I

THEORETICAL CONSIDERATIONS

COSMIC ASPECTS OF GEOLOGY.—Scientific investigations since the close of last century have now established certain conceptions of so fundamental a nature in regard to matter and energy that some mention of the present views of astronomers and physical chemists cannot be out of place in any book on engineering geology. These modern conceptions are most naturally introduced by a brief account of the place of the sun in the universe and our place in the sun's system. It is the opinion of astronomers that the sun is one of the 30,000 or so million stars which constitute the galaxy we call the Milky Way, which itself, like a vast fairy wheel, is revolving in the heavens. The diameter of the Milky Way system is so great that light travelling at 186,000 miles per second takes 200,000 years to traverse it. The sun is at a distance of 40,000 years (light years) from the hub of the Milky Way, and moves with it, travelling at 200 miles a second, to accomplish a revolution in about 250 million years. But this is only one of the thousands of similar star systems, for, according to Sir James Jeans, nebulæ have been revealed, by photographs taken with a 100-inch astronomical telescope, at distances up to 140,000,000 light years, and ascertained to be speeding outwards at more than 12,000 miles per second. And in the space within there are stated to be 2,000,000 nebulæ at intervals of 1,800,000 light years from each other, some 2,000 to 3,500 times the weight of the sun, and each capable of producing a galaxy like the Milky Way.

The star next nearest the sun is 275,000 times the distance of the earth from the sun (93 million miles), while Sirius A, the brightest star we see, is far larger than the sun, although only 2.45 times its weight, and 26 times brighter than our luminary. Its twin, the "white dwarf," Sirius B, is 26/10,000 less luminous than the sun, and, although 0.85 times the weight of the sun, said to be no larger than the earth. It is a curiosity, like Van Maanen's star, which is also stated to be of remarkable constitution—for its mean density is more than 50,000 times that of water, and thus over 2,000 times as dense as platinum. There is no such substance known to us, as the element of

greatest atomic weight, uranium, is 238, the atomic weight of platinum being a little over 195. The star S. Doradus, in the Magellanic clouds, is reputed to be intrinsically the brightest star, and roughly 500,000 times brighter than the sun. If luminosity is associated with mass, it must also be a great star. The " red giants," Antares and Betelgeux, are believed to be of enormous size, with diameters 100 times that of the sun. Occasionally a star undergoes a change, and develops in luminosity until attaining in one case a brilliance greater than Sirius A, and so, after a period of glory, gradually resuming its original luminosity or fading to insignificance. These variable stars have been known since early times, and are evidently commoner than was once supposed. Sir James Jeans has given it as his opinion that the size of stars can rarely exceed 100 times the mass of the sun, and that they do not remain unchanged for more than 5 to 10 million million years.

On the basis of Helmholtz's theory of the condensational energy in the sun, the available supplies could not maintain its present rate of radiation for 25 million years, and Lord Kelvin showed that on a basis of secular cooling the age of the earth was roughly 20 million years. Dr. Arthur Holmes has shown that, if the heat developed in radioactive disintegration is considered, the age of the earth is far greater than if this factor is omitted, and he demonstrates that if half the heat lost is due to radioactivity, the age of the earth becomes 120 million years. The true figure is nearer 75 per cent. of the heat loss, and this takes the estimate to over 1,250 million years (actually the figure is 1,600 million years). If this is assumed conservatively as the age of the oldest sedimentary rocks, we must allow time for the oceans to collect previously, for the moon to originate from a still molten earth at an early period, and before that, again, for the disruption of the sun. If we place the age of the Solar system at 2,500 million years, which is an estimate approved by astronomers, the source of the sun's energy becomes a problem of curious character. The problem concerns every star in the heavens and, in the case of Sirius A, and more so for S. Doradus, assumes a truly transcendental aspect. It will be shown that even if the sun was entirely composed of uranium and its radioactive products, the energy available would fall far short of the required amount. The quantity of energy radiated into stellar space by the sun alone is of the order of 50 horse-power continuously from every square inch of its vast surface. The fraction which reaches the earth in one year alone is equivalent to burning 4×10^{23} tons of anthracite.

Sir Arthur Eddington has drawn attention to the general relation that appears to exist between the mass and luminosity of main-series stars of absolute magnitudes from -4 to $+11$. Astronomers and

mathematicians recognise this as evidence in regard to a discrete law of the theory of relativity which states that all forms of energy possess mass. From this Einstein relation of equivalence between mass and energy it follows that destruction of matter creates energy—mass is annihilated into radiation—a solution to Solar and Stellar supplies of energy is arrived at. The equation is written E equals MC^2 where E is the radiation (energy), M is the mass annihilated and C the velocity of light. Sir James Jeans arrives at the computation that one gram of mass carries 9×10^{20} ergs or 2.15×10^{13} calories of radiation. From the data available for the rate of the sun's radiation, it is shown later that the supply of energy represented by the mass of the sun is practically inexhaustible, and that it maintains its condition for more than 7.5 million million years—the estimated lifetime of a star. What is true of the sun is presumably true for stars of similar character. The importance of this relation is realised when it is referred to terms of a lb. of coal, for, as Jeans states, the *annihilation* of 1 lb. of coal into radiation is equivalent to the *combustion* of 5 million tons of similar coal; an ounce of coal annihilated into energy would provide locomotive power for all the railways in Great Britain. The proof of this law will be of far more profound influence in the civilised world than the discovery of radioactivity and the real constitution of the atom. The steady infall of the highly-penetrating cosmic rays from interstellar space suggests that perhaps matter is reconstructed there on the basis of the quantum of light. The relation given in this connection is $\epsilon\lambda = hC$ where h is Plancks constant (6.55×10^{-24} ergs), ϵ energy absorbed by atom, λ the wavelength, and C the velocity of light. The quantity of energy given in the above relation is called the quantum of light of wavelength λ.

THE SOLAR SYSTEM.—The attractive nebular hypothesis put forward by Laplace nearly 150 years ago has for various astronomical reason's failed to account fully for the origin of the sun's planetary system. And the ingenious theory of meteorites, suggested by Sir Normal Lockyer nearly 50 years ago, was also put aside for the planetesimal hypothesis advanced by Chamberlain and Moulton early this century. Analysed from a thermal aspect, it appears to mathematicians to have serious flaws, in consequence of which the tidal theory of Jeans, as modified with his consent by Dr. Harold Jeffreys, appears to-day to be the most satisfactory. All these theories agree that the materials of the planets were derived from the sun, which previously had been an encumbered star. The tidal theory has a fundamental assumption—that a star, larger than the sun, almost came into collision with it. The passage of this star was so close and so rapid that the incandescent matter it displaced by tidal

action from the sun, with the departure of the star, remained in the Solar envelope. The far-flung, attenuated and incandescent matter displaced from the sun's body evidently condensed into molten bodies and rapidly assumed the primary form of the various planets—from the outermost, Pluto, to the nearest, Mercury. In the case of the earth, it is believed that solidification probably ensued within 15,000 years of the sun's disruption, and that, almost in the act of solidification, the disturbing tidal influence by the sun, rendered disruptive by resonance, led to the birth of the moon from what is now the hollow of the Pacific. Astronomical reasoning, on the basis of the eccentricity of the orbit of Mercury, places the formation of the planetary bodies at about 10^9 to 10^{10} years ago. Both in its mode of origin and in possessing a planetary system, the Solar system is unique, and, so far as we are concerned, our earth is the centre of the universe.

The sizes of the various planets and their distances from the sun, their axial rotation and period of travel in their orbits around the sun are fairly well known and established. It is sometimes not fully appreciated that the great planets—Jupiter, Saturn, Uranus and Neptune—lie beyond the belt of the asteroids, and that though they are vastly greater in mass than any of the inner planets—Mars, the Earth, Venus and Mercury—they are barely one-fourth the density of those of the inner planets. The mean density of the sun is similar to that of Jupiter, roughly that of coal (sp. gr. 1.4), whereas that of the earth is 5.6, approximately heavier than the heaviest iron ore (hematite). Pluto, beyond Neptune, is quite 3,000 million miles from the sun; Jupiter is nearly 500 million miles; the earth barely 93 million miles; and Mercury about 36 million miles. The sun's diameter is estimated at nearly 860,000 miles, which is 10 times that of Jupiter, the greatest planet, and over 100 times the diameter of the earth. The meteorites which fall on the earth reveal that they do not contain any elements unknown in the earth, and that they are very similar to rocks—basic and ultra-basic rocks—with which we are familiar. An examination of the sun by means of the spectroscope has shown that, in the parts visible to us, the same elements occur there as here. Of the 90 elements known to us, 61 have been identified in the sun—hydrogen predominating, probably to the extent of 90 per cent. Of the remaining 29 there are 13 whose spectrum lines are not visible, 14 more require further tests for decision, and 4 only, chiefly very rare elements such as radium, have not been detected in the sun. In fact the evidence suggests that, except for hydrogen, the elements are present in, roughly, the same proportions as in the rocks of the earth. Hence, although uranium has been detected, it is not

surprising that radium—more than 3 million times rarer—has so far not been identified.

The face of the sun normally seen is the incandescent surface of the so-called photosphere, which is estimated to be at a temperature of nearly 6,000° C. The main body of the sun is never visible, but during an eclipse of the sun the chromosphere, corona and solar prominences are evident, and extend the gaseous materials of the sun, including many metals, far into space. Including the atmosphere, the sun's true volume is far larger than that arrived at from the diameter of the photosphere. Professor H. N. Russell has estimated the following amounts of various elements, in tons, per square mile of the sun's atmosphere: magnesium, 350; iron, 250; silicon, 150; sodium, 100; potassium, 50; carbon, 50; aluminium, 15; nickel, 15; manganese, 10; cobalt, 6; chromium, 6; titanium, 2; vanadium, 1.5; copper, 1.5; zinc, 1; and all others under 0.2. These data indicate that uranium is as rare a constituent in the sun's materials as in the earth, but, as will appear later, even if the sun was entirely composed of uranium, the heat evolved as a result of its atomic disruption (radioactivity) would fall far short of the energy being lavishly radiated from the sun. Jeffreys assumes that 0.03 calories per second are received per square centimetre of the earth's surface (normal to the sun), and from this, with a distance of 1.5×10^{13} centimetres from the earth, calculates the sun's rate of radiation as 3.3×10^{33} ergs per second. Put in other words, the sun is radiating energy at the rate of 50 horsepower from each square inch of its surface, while we are receiving about one horse-power per square yard of the earth's surface from the sun. Jeffreys shows further that the energy radiated from the sun is equivalent to 3.7×10^{12} grams per second, and at this rate the loss of mass in the sun during 10^{10} years would equal 10^{30} grams, roughly 1/2000 the sun mass, which in a period of 1,500 million years (geological time) would hardly be perceptible.

A close examination of the sun's radiation in regard to the quantity received by the earth shows that the ozone layer in the outer atmosphere removes (absorbs) the extreme ultra-violet rays, and that the carbon dioxide and moisture in the atmosphere also absorbs some of the energy. The effects noticed on magnetic instruments and in the reception of radio-transmission during sun spot activity show that the solar radiation affects or includes the whole gamut of æther waves from the long to the short wireless waves, and so, through those of a centimetre or so, to, successively, the infra-red (10^{-1} to 8×10^{-5}), visible light (8×10^{-5} to 4×10^{-5}), ultra-violet ($4 \times 10^{-5} \times 10^{-7}$), and even beyond the gamma rays (1.4×10^{-8} to 5×10^{-11}), with wavelengths mere fractions of a millimetre. There can be no question that the

surface temperature (climate) of the earth has been controlled by the sun's warmth, almost from the moment the crust was formed. Of evidence of legacies from remote geological ages we have the petroleum occurrences and great coalfields—the former the product of an infinitesimal part of the animals that lived by the sun's warmth, and the latter an equally insignificant part of the vegetation which flourished in the sunshine millions of years ago. Almost every stream and glacier represents the water once evaporated by the sun and carried to the land as vapour, and there precipitated as rain or snow. And these are effects visible to all.

THE EARTH AND MOON.—More than 50 years ago Sir G. H. Darwin advanced the Tidal theory, that the Moon originated from the Earth, owing to the Sun's influence. The original hypothesis has been amplified by Jeffreys, who has suggested that the tidal forces would be greatly developed by the phenomenon of resonance, whence his theory is known as the Resonance (Tidal) hypothesis. Jeffreys shows that the solidification of the earth took place rapidly from a molten condition, and that the disruption of the earth, giving rise to the moon, must have occurred at the time of solidification. He indicates the Pacific basin as the hollow from which the Moon was derived, and this supports his contention of the solidification of the earth, as otherwise such a scar in a rotating body could not have persisted for nearly 2,000 to 2,500 million years. At that pre-lunar epoch the length of the day was only 5 hours, but in a relatively short time, 2,000 to 1,500 million years ago, after the birth of the Moon, when the oceans were in progress of accumulation and the earliest sedimentary rocks were being deposited, the day had lengthened to about 20 hours. Since then the axial rotation has gradually slowed down, until the present time, when the day is almost exactly 24 hours. Although many geologists find it difficult to accept the view that the scar we call the Pacific basin could have persisted since the dawn of geological time, there is geodetic data in support of it. Measurements made at the close of last century by Capt. A. R. Clarke, R.E., indicate that the equitorial diameter from the Gulf of Guinea (14° 23′ E.) to the mid-Pacific (194° 23′ E.) was 2 miles longer than that at right angles to it from the Indian Ocean (104° 23′ E.) to near the Galapagos Islands (284° 23′ E.). These differences * indicate that the globe is not a true spheroid of rotation.

The velocity of the Earth's surface, due to axial rotation, is over 1,000 miles an hour, and the travel of the Earth along its orbit round the Sun is above 1,000 miles a minute. As part of the Solar system,

* William Bowie is of the opinion that the difference can hardly be 100 metres and other geodetic investigators accept as much as 1,000 metres.

it moves with the Sun along the Milky Way at 200 miles a second. The Sun has more than 1,250,000 times the volume of the Earth, which in turn is nearly 50 times the volume of the Moon, but, whereas the mean density of the Sun is 1.4, and of the Earth 5.6, that of the Moon is 3.4, which is greater than any of the rocks, though less than that of garnet. The Moon's distance from the Earth is nearly 240,000 miles, and its diameter only 2,160 miles, as against 7,925 miles of the Earth. Lunar craters are a characteristic feature of the Moon's surface, clearly indicating violent volcanic action in times past, though all now seems at rest. Since the Moon is clearly composed of material from the Earth, it is concluded that radioactivity has played a part in the Moon's thermal history. There seem to be no mountain ranges on the Moon similar to the belts of folded rocks which constitute the Alps, the Himalaya, and similar orographic features. It is presumed from this that, whereas the Earth continues to lose internal heat and to contract, the Moon is probably cold and not subject to crustal contraction. The chief influence of the Moon on the Earth is the production of ocean tides which, when the Sun and Moon are in conjunction or opposition, are highest and most active in coast erosion, deltaic growth and river flushing.

The prevailing opinion, supported by mathematical examination, is that the Earth must be considered as a solid body, and that it is steadily, though slowly, losing heat, and thus subject to contraction. The radioactive elements seem to be concentrated in the outer rocky shell, but the heat evolved is in general dissipated without increasing, except, perhaps, locally, the temperature of the enclosing rocks. This view excludes an extremely interesting theory advanced by Professor J. Joly, whereby he suggested a steady accumulation of heat, a periodic melting of a subcrustal layer in consequence, and volcanic eruptions and surface changes as a result. This view also excludes the possibility of the existence of a continuous plastic or fluidheated layer on which the actual crustal rocks rest and on which the continents float, so that theories which involve the drifting of continents cannot seriously be entertained. These points will be discussed on a later page. They are merely mentioned here, as is also the subject of the stability of the Earth's surface in relation to its axis of rotation. For all practical considerations the solid Earth has a very slight "wobble" on its aixis (or the axis has a little "play"), but this does not develop into any serious change of axial position, *e.g.* a polar position gradually changing into an equatorial position. As will be seen later, the curious geographical changes, as noted in geological evidence of past times, will be found due to vertical crustal movements, and are chiefly the results of loss of heat and crustal contraction.

CONSTITUTION OF THE EARTH.—Although there has been much speculation regarding the internal structure and composition of the Earth, we know actually very little. Seismological studies suggest that to a depth of about 1,800 miles (2,900 kilometres) there is a solid shell below which the *S* (distortional) waves apparently do not go. This has given rise to the belief in a molten core of high (12) density material—probably Iron-Nickel—under great pressure. Above this core the shell appears to be in concentric layers, evidently rather sharply distinct, at depths of 750 miles (1,200 kilometres) and 37 to 40 miles (60 kilometres) from the surface. In older writings the outer and middle shells were generally referred to as the *SIAL* and *SIMA*, respectively—the *SIAL*, supposed to consist largely of *Si*lica and *Al*umina, was thought to float on the lower, which consisted chiefly of *Si*lica and *Ma*gnesia. The general opinion to-day is that a Granite layer about 7 to 8 miles (10 kilometres) thick constitutes the outermost shell or crust. It is chiefly present in the Continental areas, and appears to be entirely absent in the Pacific basin. The mean density of the rock is 2.64, and the temperature attained at 10 kilometres is roughly 450° C. The radioactive elements are largely concentrated in this Granite crust. Immediately below it, to a total depth of 24 miles (37 kilometres) from the surface, there follow layers of tachylitic basalt with a density of about 2.85, and attaining near its basal level a temperature of 1,250° C. Below this, again, and extending to a total depth of 37 miles (60 kilometres) from the surface, and thus completing the main outer shell, is a layer of dunite, of density 3.3 to 4.0, due to pressure, and probably at a temperature of 2,000° C. Below this, again, and to the next marked discontinuity at 750 miles (1,200 kilometres) is Dr. L. L. Fermor's Infra-Plutonic zone or the middle shell, followed below by the inner shell of three transition layers to 1,800 miles (2,900 kilometres) round the fluid core.

The travel of the primary (*P* or "push," compressional) and secondary (*S* or "shake," distortional) seismic waves increases steadily in velocity and then falls off near the base of the inner shell (2,900 kilometres), as shown below:

	P km./sec.	S km./sec.
Granite layer	5.4 to 5.6	3.3
Basalt layer	6.2 to 6.3	3.7
Dunite layer	7.8	4.3
Middle shell .. .. } Inner shell .. .. }	13.0	7.2
Core	8.5	?

Corresponding with these layers and the velocities of the two types of seismic waves which prove that the entire shell must be solid, we have

Barrell's conclusions as regards the strength of the shell. He considers that to a depth of about 20 miles, i.e. nearly the base of the basalt layer, the shell is very, very strong, and then weakens rapidly, and that from below the base of the dunite (60 to 100 kilometre depth) to about 250 miles (400 kilometres) occurs his Asthenosphere or zone of weakness. The temperature and pressure in this Asthenosphere would be so great that any material in it would probably behave as though plastic and liquify with release of pressure. There is good reason to believe that radioactive elements are practically absent below the dunite layer (60 kilometres). It is concluded from these statements that mountains do not float, nor can the idea of Continental Drift be taken seriously as a working hypothesis. Nor is there evidence in support of a continuous molten layer which becomes fluid at least periodically (50 million years) as the result of heat accumulation from radioactive causes.

The following table (" Elements of Geophysics," by Ambronn, translated by M. Cobb, 1928, p. 267) gives the thermal conductivity of various rocks and minerals.

γ denotes the amount of heat in gram calories which flows in one second through a cross-section of one square centimetre, if the temperature gradient is 1° C. in one centimetre.

$\lambda \times 10^{-3}$ measured dry.

Very fine sand	0.3	"
Quartz sand	0.6	"
Coal	0.8	"
Snow	1.1	"
Water	1.4	"
Glass	2.1	"
Clay	2.5	"
Andesite	3.1	"
Granite	4.0	"
Limestone	5.2	"
Porphyry	5.5	"
Phyllite	5.9	"
Sandstone	6.0	"
Slate	6.1	"
Quartz	6.2	"
Rock Salt	6.6 (?)	"
Magnetite	30.0	"

Moist granites, gneisses, etc., conduct 10% better, and in the case of clays and other rocks the thermal conductivity may be 100% greater if the rock is moist.

The melting points and densities of various rocks are given on the following page.

Name	Density *	Melting point †
Obsidian	2.33 to 2.41	—
Granite	2.64	1,000° C.
Grano-diorite ..	2.73	—
Syenite	2.78	1,100° C.
Diorite	2.85	1,200° C.
Basalt	2.85	—
Gabbro	2.94	1,250° C.
Peridotite	3.18	—
Dunite	3.30	1,500° C.
Eclogite	3.40	—
Clays	1.85	—
Shales	2.24	—
Slate	2.77	—
Sands	1.30 to 1.80	—
Sandstone	1.90 to 2.20	—
Quartzite	2.60	—
Portland Stone ..	2.37	—
Limestone	2.48 to 2.53	—
Marble	2.70	—

RADIOACTIVITY.—Rontgen's discovery of the X-rays in 1895, as the result of passing electric discharges through a vacuum tube, was at first ascribed to the phosphorescence of the glass which was visible. Becqueral, in 1896, while testing such phosphorescent substances, somewhat accidentally discovered that Uranium salts evolve similar rays under all conditions, and continuously. He thus discovered radioactivity, but it was Mme. Curie, who, with M. Curie, by 1898 had isolated Polonium and Radium from Pitchblende, stated that this peculiar property of Uranium, Polonium and Radium was a fundamental atomic character of the atom, and that no outside influence could increase, retard or stop it. Thorium and Actinium were discovered to be radioactive elements very soon after. It was found that it required roughly 10 million parts of Uranium to yield 3 parts of Radium by weight, and that this proportion is a fixed ratio between these two elements. Investigation also showed that the rays emitted from Radium were of three kinds—named α, β and γ rays—which possessed very marked differences. The α rays are positively charged atoms of Helium, and cannot penetrate a sheet of paper, and are only slightly deflected by a magnetic field. The β rays are negatively charged electrons, and can penetrate tin or aluminium foil, and are easily

* It must be added that under great pressure all these figures are subject to increase.

† After J. H. L. Vogt (Econ. Geol., vol. 21, 1926). It is known that some granites have crystallised at about 500 C or below and that the lava of Hawai (Kilauea) remains soft at 800 C. Laboratory determinations do not include gaseous matter, steam, pressure or time; so that these figures are not very helpful. They show that the Acid rocks have a *lower* melting point than the Basic rocks, which seems to be in agreement with observations.

deflected by a magnetic field. The γ rays have great penetrating power, and are not deflected by a magnetic field. The discovery was early made that radioactive substances evolve heat, evidently in connection with the emission of the α particles of Helium, and that in the case of Uranium the amount was 8.5×10^{-5} calories per hour per gram, while with one gram of Radium the quantity would be no less than 133 calories per hour or 1,160,000 calories in a year. As its average life is 2,400 years, the total heat evolved from one gram of Radium is about 2.9×10^9 calories—a million times greater than any other substance; for, as Professor Soddy has shown, one gram of coal yields 8,000 calories on combustion with 2.7 grams of oxygen, so that a total of 3.7 grams of matter yields 8,000 calories, and one thus yields only 2,200 calories.

To Sir Ernest Rutherford and Professor Frederick Soddy must be given the credit of first stating that these phenomena already mentioned accompanied a process that the alchemist had been seeking since the dawn of civilization—the transmutation of elements. Here it was spontaneously at work, and had been ceaselessly in operation since the origin of the Earth. As defined to-day—a substance is radioactive when the atoms of which it is composed disintegrate spontaneously, regardless of whether or not the emission of rays can be detected in the process.

There are now known to be about 40 radioactive elements, but they really belong to three series, each sequence traceable to the original parents, Uranium, Thorium and Actinium, which is considered to be a branch from Uranium as a source. Omitting several intermediate steps (elements), the disintegration products of the Uranium series are shown below:

Elements formed successively	Atomic Weight Oxygen —16	Half Period life	Proportion in 1 ton of Uranium	Emission (ray)
Uranium I ..	238	4.5×10^9 years	1,000,000 grams	one α
Uranium II ..	234	(?) 10^6 years	(?) 250 grams	,, α
Ionium	230	7.6×10^4 years	25 grams	,, α
Radium	226	1,600 years	312.5 milligrams	,, α
Radon (Emanation)	222	3.825 days	1/500 ,,	,, α
Radium A ..	218	3.05 minutes	one millionth m.g.	,, α
,, B ..	214	26.8 ,,	nine ,, ,,	,, β
,, C ..	214	19.7 ,,	seven ,, ,,	,, α
Radium D ..	210	25 years	3 milligrams	,, β
,, E ..	210	5 days	1/4000 milligram	,, β
F (Polonium)	210	136.3 days	1/14 milligram	,, α
,, G (Lead)	206	stable		

Professor Soddy (" The Interpretation of the Atom," 1932) states (p. 72):

" One of the most helpful ways of regarding a radioactive disintegration series is by hydraulic analogy. Instead of the succession of products, we may suppose there is a succession of reservoirs of equal area and with vertical walls, connected in series by pipes. We may suppose each reservoir has at the bottom an outlet filter, from which the water oozes or percolates out over a large area and then flows through a pipe into the top of the reservoir next in the series. Under these conditions, the rate of flow of water is simply proportional to the head or height of water in the reservoir, and as this has vertical sides, to the quantity of water in the reservoir. We thus arrive easily at the fundamental law of the disintegration series, that for each member the rate at which it is supplied depends not at all on how much is already present, but only on how much of its immediate parent is present, whereas the rate at which it itself is changing is proportional to the amount of it present. Each reservoir in the system is losing water at rate proportional to the amount of water in it, and is gaining water at a rate proportional to the amount of water in the reservoir preceding it in the series. . . . It is easy to understand, with such an analogy, the condition of radioactive equilibrium, such as naturally exists in a Uranium mineral. The first reservoir, corresponding with Uranium, is so enormous and the overflow from it so small, that it may go on . . . for millions of years. Under such circumstances the whole series must be in a steady state. . . . Those with large outlets will need only a small head . . . and those with small outlets will need a pıoportionally large head. . . ."

The Radium reservoir has a very small outlet—sufficient to allow only 1/2300 of its content to discharge in a year.

The Thorium and Actinium series of radioactive disintegration is very similar to that of Uranium, which is the longest. The term " half period change " is employed for the time in which the radioelements disintegrate to half their amount when alone. Thus Radon, the gaseous emanation derived from Radium, becomes, when freed from Radium (its source of supply) half its total in under 4 days, and only a quarter remains after about 8 days, and there is barely onesixteenth left after a fortnight. It disintegrates to Radium A and this, through Radium B and C, rapidly to Radium D. Sir James Jeans estimates that one gram of Uranium in the fulness of time would yield 0.8653 grams of Lead, 0.1345 grams of Helium, and that the difference 0.0002 grams would disappear as radiation. The end products of the Thorium and Actinium series are also forms of lead—i.e. chemically *lead*, but they have different atomic weights—Radium G 206, Actinium D 207 and Thorium D 208—and once mixed cannot again be separated by any chemical means—the product behaves as a single chemical element although constituted as stated. W. F. Aston

has shown that almost all the elements we know are mixtures of the same type—tin has no less than eleven isotopes, as the true individual elements in these mixed elements are called. Thus Ionium, the parent of Radium, is isotopic with Thorium, and Radium and Mesothorium are isotopes. It is evident that if in an Uranium-bearing rock only Radium G (lead) was present, we have, from the proportion of these two elements, the means of evaluating the time that has elapsed. And, if the Helium given off throughout the establishment of the disintegration series was retained in the rock, the proportion of Helium to Uranium would furnish data for estimating time. The same is of course true for Thorium D and Thorium or Helium and Thorium, if no Uranium is present. But, normally, allowance must be made for isotopic lead and the presence of both Uraniun and Thorium. The Helium method is a good check, as it must always give a minimum age. In a normal way, assuming both Uranium and Thorium present, Jeffreys gives the formula for age as equal to $Cz/(x-0.35y)$, where $C = 7.37 \times 10^9$ years, z = grams of lead, x = grams of Uranium, and y = grams of Thorium.

Estimates based on the ratios Uranium/lead, and assuming the proportions of Uranium, Thorium and lead in average igneous rocks to be 6×10^{-6}, 15×10^{-6} and 7.5×10^{-6}, respectively, Jeffreys estimates, on the basis of all the lead being from a Uranium source, an age of 5,700 million years for the rock of the Earth's crust. Allowing for the Thorium, Holmes reduces this estimate to 3,200 million years, and Aston, allowing for the isotopic nature of the lead (206,207 and 208 atomic weights) in the proportions 4 : 3 : 7, further reduces the estimate to 2,000 million years. The proportions of Uranium, Thorium and Potassium, which is feebly radioactive, in different igneous rocks, together with the heat evolved in them in calories per second per gram of rock, in consequence of radioactivity, is shown below (after Jeffreys "The Earth," 2nd Edn., 1929, p. 143).

Rock		Uranium	Thorium	Potassium	Total Heat
Granite	%	9.0×10^{-6}	20×10^{-6}	3.4×10^{-6}	
	heat	22×10^{-14}	14×10^{-14}	13×10^{-14}	49×10^{-14}
Diorite	%	6.6×10^{-6}	6.1×10^{-6}	2.2×10^{-6}	
	heat	16.5×10^{-14}	4.4×10^{-14}	8.5×10^{-14}	29×10^{-14}
Basalt	%	3.5×10^{-6}	7.7×10^{-6}	0.76×10^{-6}	
(dolerite)	heat	8.7×10^{-14}	5.5×10^{-14}	2.9×10^{-14}	17×10^{-14}
Plateau	%	2.2×10^{-6}	5.0×10^{-6}	0.80×10^{-6}	
basalt	heat	5.5×10^{-14}	3.6×10^{-14}	3.1×10^{-14}	12×10^{-14}
Dunite	%	1.4×10^{-6}	$1,0 \times 10^{-6}$	?	
	heat	3.5×10^{-14}	0.7×10^{-14}	?	4×10^{-14}

The diminutions in the proportions of Uranium, Thorium, and even Potassium, in the rocks from the Acid (Granites) to the Ultra-Basic (Dunites) is further supported by the evidence of the meteorites. The Stone meteorites, which correspond to Ultra-Basic rocks, have 0.25×10^{-12} grams of Radium per gram of rock, compared with 3.0×10^{-12} in Acid rocks, 2.0×10^{-12} in the Intermediate rocks, 1.0×10^{-12} in Basic rocks, and 0.5×10^{-12} in Ultra-Basic rocks, whereas Iron meteorites contain no detectable quantity of Radium. This evidence is in support of the idea that the radioactive elements are present only in the upper shell of the earth, because, if they were uniformly distributed throughout the substance of the earth in anything like the amount they are in Granite, the internal heat of the Earth must increase. As an average, the rate of transfer of heat upwards through the strata is estimated at 2.4×10^{-6} calories per second per square centimetre. This could readily be supplied by a granite layer, nearly 12 miles (19 kilometres) thick, presuming the radioactive materials to be in the proportions estimated. There is some doubt both as to the thickness of this granite layer and the amount of the radioelements at that depth, but the opinion prevails that the internal heat of the Earth is distinct from radioactive sources, and that the Earth's temperature gradient, although greatly, is not entirely maintained by radioactivity. In certain cases, as with the surprising temperatures encountered in driving the Simplon tunnel, the heat was by Professor J. Joly directly traced to the radioactive elements present in the rocks. Thus, seeing that Radium always occurs in nature in association with Uranium, and that it is always in the ratio 1 : 3,300,000 with this parent, it is unlikely there can be a large amount of Radium in the Sun. If that luminary were entirely composed of Uranium, the heat evolved would not maintain its stupendous radiation.

THE AGE OF THE EARTH.—The Sun had been a star before the Solar system began, roughly 2,500 million years ago, and the Moon, if derived from the Earth, originated soon after, just at the time the Earth solidified and before the oceans came into being. Geological time is reckoned from the oldest known sedimentary rocks, which are older than some intrusive rocks, whose age, on radioactive data, is estimated at more than 1,250 to 1,300 million years. We may, therefore, accept an age of 1,500 to 1,600 million years as that of the oceans and the earliest sedimentary rocks and the beginning of geological time. It is but 1/500,000 the period of the lifetime of a star, and yet there are still many who, while discarding Lord Kelvin's estimate, based on secular cooling, of 20 million years, consider 80 to 100 million years as the probable age of the Earth. Calculating from the amount of sodium carried annually to the ocean and the total there, they

estimate a maximum of 120 million years as the age of the oceans, and thus conclude that the methods based on radioactive disintegration give ten times the true age. The problem of sodium involves that of salt, and so includes the question of the chlorine, which, as is well known, constitutes one of the mysteries of geology—there is far more chlorine in the sea than could be supplied from the available rocks of the Earth's crust. There are also other details relating to the method of sodium determination which entirely vitiates it. And as regards estimates based on the accumulation of sediments, there are almost equally serious objections. Holmes quotes the total thickness of all sedimentary deposits as 73,000 feet for the Cainozoic, 86,000 feet Mesozoic, 90,000 feet Upper Palæozoic, 95,000 feet Lower Palæozoic and 170,000 feet for the Eozoic and Azoic or Pre-Cambrian sediments. Based on a fixed rate of deposition of one foot in 880 years and a total thickness of 514,000 feet, the estimate of age is 400 million years. But the method is almost empirical—sands are deposited far more quickly, and it is impossible to gauge the time for marine limestones and to allow adequately for periods of no deposition.

As has been shown by various authorities, there are several ways along which a radioactive method of estimation can be applied. The first is that of modifying Lord Kelvin's estimate whereby the period of cooling is prolonged. If the heat lost by the earth is 2.4×10^{-6} cal/cm^2/sec. (calories per second per square centimetre), it is largely due to radioactive supplies which are 2×10^{-6} cal/cm^2/sec., *i.e.* roughly 75 per cent., and, according to Holmes (*Proc. Geol. Assoc.*, XXVI, Pt. 5, 1915), the age becomes 1,600 million years. The same writer has given data based on the Helium in Zircons from various formations which are very unreliable except in assigning relative ages. This was also found true by Lord Rayleigh in the case of Helium in Beryls from various formations. It is hardly to be expected that in the great lapse of time a gas, so inert as Helium, would accumulate without leakage. Even so, the estimates of age for the older rocks are greater than by the denudation methods previously discussed. In using the method of Pleochroic Haloes (based on their diameter and intensity of colour) in micas and fluospar, the Leinster granite (Devonian) of County Carlow was given an age of over 400 million years. The estimates based on the ratio of Lead/Uranium and Lead/Thorium are easily the most reliable, as care can now be taken in ascertaining the nature of the Lead. By this method Holmes and Lawson, working with samples from known formations, made the following determinations of Geological Age:

Late Oligocene	..	37	million years.
Late Cretaceous (?)	..	59	,, ,,
Permo Carboniferous	..	204	,, ,,
Permian to Devonian	..	239/374	,, ,,
Late Pre-Cambrian (?)	..	587	,, ,,
Upper Pre-Cambrian	..	640	,, ,,
Middle Pre-Cambrian	..	987/1,087	,, ,,
Lower Pre-Cambrian	..	1,257	,, ,,

With these data for guidance, the following table has been compiled to represent the opinions of geologists regarding the approximate age of the sedimentary formations in the Geological Record:

Era	Period	Approx. Age (Years age)		
	Recent	(Man) ½	million	years ago.
	Pleistocene			
	Pliocene			
Cainozoic or	Miocene	*30	,,	,,
Tertiary	Oligocene			
	Eocene	60	,,	,,
	Cretaceous	100	,,	,,
Mesozoic or	Jurassic	150	,,	,,
Secondary	Triassic	180	,,	,,
	Permian	*200	,,	,,
	Carboniferous	300	,,	,,
Palæozoic or	Devonian	400	,,	,,
Primary	Silurian	*450	,,	,,
	Ordovician	500	,,	,,
	Cambrian	*600	,,	,,
Eozoic	Purana or Pre-Cambrian	1,200	,,	,,
Azoic	Archæan	1,500	,,	,,

VULCANISM.—A rise in temperature, averaging 1° C. for 100 feet descent or, roughly, 50° C. for every mile (32° for each kilometre) has been noted in the rocks of the Earth's crust. This has been confirmed by the conditions found in most deep mines, and particularly in the deepest—6,000 to 7,000 feet below the surface. This evidence of internal heat is also supplied by the frequent occurrence of hot springs, of geysers, and of eruptions of lava in a molten condition. Assuming the temperature gradient above mentioned, it would appear that the basalt at a depth of 24 miles must be heated above its normal melting point, and the same is true for the dunite at a depth of 37 miles (see Fig. 8). Seismologists, however, are emphatic that the Earth's shell, down to a depth of 1,800 miles, behaves as a solid, as the distortional S waves are transmitted (see Fig. 14). Barrell's weak zone or Asthenosphere begins below the dunite layer, and he suggests

* These are periods of great crustal movement and volcanic activity.

that the strongest part of the shell is that occupied by the basalt and granite layers. It had previously been suggested that the temperature gradient in the strata indicates the passage upward of only a part of the heat liberated by the disintegration of the radioactive elements. Further, that heat accumulates in the crustal layers and—periodically every 50 million years—results in the basaltic material becoming molten. Jeffreys (" The Earth," 2nd Edn., 1929, p. 144) has examined the evidence, and concludes that, as already shown, the heat evolved from radioactive sources is less than the heat transmitted upwards through the rocks. There is thus evidence in support of a steady loss of internal heat.

As shown in the Geological Record (see p. 18), there have been at least four periods, since the beginning of the Palæozoic era, of crustal deformation accompanied by volcanic activity. In the last revolution the tectonic movements are traceable to the great outpourings of basaltic lavas of the Deccan trap, in India, and the tertiary eruptions of similar material in Europe and America. To-day the Deccan traps still cover 200,000 square miles, to an average depth of 1,000 feet, which is certainly less than half the original extent and thickness of these lave flows. They were erupted from faults and fissures and, in general, without violence, until the close of the volcanic epoch. The volume of molten material thus transferred from the basaltic layer, at a depth of, say, 20 miles, to the surface was very considerable, and it is not surprising that the area of the Arabian Sea, which before was land, sank as part of a great subsidence. It requires little imagination to see in these volcanic forces clear evidence of the emergence of molten basalt from what is stated to be a solid layer 10 to 20 miles below the surface. As the seismological evidence is of a reliable kind, and the heat of radioactive disintegration is not the cause of the melting, we must consider the loss of heat from the core upwards.

Continuous loss of heat must lead to contraction in the various layers, and each layer of the shell thus tends to become separated from the next below, due to its shrinkage. The final adjustment eventually comes to the last upper layers—the outer granite on the inner basalt—and is of a twofold character. If the basalt shrinks inwards, as it must do at least locally, there is release of pressure. If the granite layer does not shrink *pari passu*, the basalt will melt. Again, if the granite layer is left locally unsupported, it becomes subject to shearing and compressive stresses, which ultimately leads to the shearing and folding of the rocks, and results in subsidence or elevation of the surface. Thus, on the one hand sub-crustal pockets of molten magma are prepared, and on the other fissures and vents are opened for its escape upwards, and there is aggravation of the subsidences and

subsequent surface alterations. As the upper part of the granite layer cannot contract appreciably by cooling, it must tend to become separated from the basaltic layer below it.

The above explanation cannot apply to disastrous volcanic explosions such as those of Krakatoa or St. Pierre, nor, in fact, to the normal Vesuvian type of volcano. In these cases water seems to play a considerable part, both in lowering the fusing point of the lava, when under pressure, and in keeping the vent open. It is not difficult to imagine the effect of water on highly heated lava in causing an explosion; but it is a more subtle point that, where the steam cannot escape and becomes incorporated in the highly heated lava, the latter becomes more fluid. The corrosive action of certain slags on the lining of furnaces is well known, and suggests the activity within volcanoes, until ultimately renewed eruptions occur or all activity gradually disappears. The explosion of Krakatoa, though on a stupendous scale, caused only a very small earthquake, and this is not an abnormal condition of somewhat superficial volcanic activity. The explosion of nearly 4,500 tons of the double salt, $2NH_4NO_3$ $(NH_4)_2 SO_4$, of the Badische Analin und Sodafabrik, at Oppau, Bavaria, on the 21st September, 1921, gave tremors which were picked up to a distance of 227 miles only, yet the force liberated, assuming the heat of decomposition of NH_4NO_3 to be 7,500 calories per gram molecule, was, according to Jeffreys, about 1.5×10^{12} calories or 6×10^{19} ergs—dissipated chiefly into the air as sound waves.

CHAPTER II

COMMON ROCK-FORMING MINERALS

GENERAL REMARKS.—Private, neatly-labelled collections of minerals are more frequently kept and examined than is often supposed. In some cases the petrological names have proved a difficulty, and more popular names, such as greenstone, whinstone, etc., have been used. In this connection considerable assistance is available in the form of two useful books, " Elements of Mineralogy," by F. Rutley, revised in 1918 by H. H. Reid, and " The Nomenclature of Petrology," by Arthur Holmes. Collections of minerals and rocks become far more interesting if they are studied in a practical way, *i.e.* by determinations of specific gravity, hardness, cleavage, adhesiveness to grease, examinations of thin sections under the microscope, etc. Unfortunately the idea is prevalent that the cutting of thin slices of a rock or mineral is difficult, particularly when in camp. This is not true ; it is possible to train an intelligent servant to cut sections in two or three months. The apparatus required is simple and inexpensive. However, this aspect of the study of specimens will be discussed later.

According to the geologist :

" Rocks are aggregations of simple mineral bodies or mineral matter. The minerals which compose the various forms of rocks may occur in crystals of sufficient dimensions to allow of their individual detection with the naked eye, or they may exist in forms so minute as to render their individualisation possible only with the high powers of the microscope . . . also before it is possible to intelligently study the rock masses of the Earth's crust, it is first necessary to be acquainted with the minerals of which the rocks are composed. Minerals are aptly compared to an alphabet and the rocks to a series of words constructed therefrom." (" An Introduction to the Chemical and Physical Study of Indian Minerals," by T. H. Holland.)

DEFINITION OF A MINERAL.—" A mineral is a body produced by the processes of nature, having a definite chemical composition and, if formed under favourable conditions, a certain characteristic, molecular structure which is exhibited in its crystalline form and other physical properties." (" Text Book of Mineralogy," by E. S. Dana.)

DEFINITION OF A CRYSTAL.—" A crystal is the regular polyhedral form, bounded by smooth surfaces, which is assumed by a chemical

compound, under the action of its intermolecular forces, when passing under suitable conditions, from the state of a liquid or gas to that of a solid." (Text Book of Mineralogy," by E. S. Dana.)

Of all mineral substances, water is perhaps the most important for the support of life. In its normal liquid form it is not familiarly recognised as a mineral. It has a definite chemical composition H_2O; boils at 100° C. under a pressure of one atmosphere; assumes the solid state, as ice, at 0° C.; and has other determinable physical properties which show that it fulfils the requirements of a mineral (see definition on p. 21). A dweller in the Arctic Regions would also be justified in classing the extensive ice-sheets there found as true rock masses (see definition on p. 21). Speaking of water and ice, J. F. Kemp ("A Handbook of Rocks," 5th Edn., 1911, p. 85) says:

"There is no reason why they should not be considered igneous rocks of extremely low fusing point . . ."

There are over a thousand distinct minerals known to science, but of these only a relatively small number are in any sense abundant, and very few form the essential constituents of rocks. The most important rock-forming minerals are: (1) Orthoclase, plagioclase, and other felspars; (2) quartz; (3) augite, hornblende, olivine, and other ferro-magnesian minerals; (4) the micas, both black and white varieties; (5) magnetite, hematite, and limonite; (6) the titanium materials, rutile and ilmenite; (7) kaolin, etc.; (8) dolomite and calcite; (9) apatite, zircon, etc.; and (10) gypsum, carbon, and other substances.

PHYSICAL CHARACTERS.—The chief physical characters of the various rock-forming minerals are their (*a*) shape and structure; (*b*) form of aggregation; (*c*) cleavage; (*d*) fracture; (*e*) hardness; (*f*) tenacity; (*g*) solubility; and (*h*) behaviour when subjected to rapid changes of temperature. These characteristics largely determine the physical properties of the rocks in which they predominate.

(*a*) STRUCTURE.—By far the greater part of the mineral components of a rock consist of imperfect crystalline grains. The prevailing shapes of these particles may be: (1) elongated or of *columnar form*, such as the prisms and needles (of amphibole), bladed and acicular types (kyanite), fibrous varieties, including those with silky separable fibres (asbestos) or stellate forms (stibnite); (2) rounded and *granular*, with irregular interlocked grains (calcite in marble, see Photomicrograph No. 9); and (3) flat, sheet-like or tabular shapes (*lamellar* structure), with platey, leaf-like varieties—some straight and others curved and bent. Mica has this lamellar structure highly developed. The term *micaceous* is often used when the bulk of a rock consists of thin flakes of a particular mineral (*e.g.* micaceous hematite).

(*b*) FORM OF AGGREGATION.—Much depends on the size and condition of the mineral components; they may be large—some crystals of beryl are over a yard long and more than 18 inches across—or they may be so small as to appear invisable to the naked eye. These remarks apply to the *crystalline* grains only. The same mineral may occur in a *crypto-crystalline* condition, or it may even be *amorphous*. Quartz, chalcedony (agate) and opal are, respectively, three such forms of the substance known as silica (SiO_2). No trace of crystalline structure is visible in opal, even when it is examined under the microscope. This condition or form of a mineral substance may at times greatly influence the physical and chemical behaviour of a rock when exposed to certain atmospheric agents (weathering, etc.). It may result in the avoidance of an otherwise excellent ornamental building stone. The two substances, pyrite and marcasite, are identical in chemical composition, yet the latter oxidises far more readily in moist warm air and produces ugly brown patches on the stone.

(*c*) CLEAVAGE.—In most crystalline bodies there is a tendency, when the mineral is strained, to split easily along certain definite directions and yield smooth plane surfaces. This property or cleavage is named according to the direction of the plane of separation: for example, (1) fluorspar (Blue John) has four well-developed cleavages parallel to the faces of an octahedron; it is said to have *octahedral* cleavage; (2) calcite has three easy cleavages parallel to the faces of a rhomb, and is therefore said to possess *rhombohedral* cleavage; (3) a mineral with three cleavages at right angles to each other would have *cubic* cleavage; (4) minerals with prismatic, acicular, or fibrous structure (hornblende, kyanite, asbestos, etc.) have two well-developed cleavages parallel to the long axis of the mineral particles, consequently these minerals are said to possess *prismatic* cleavage; (5) mica has one perfect direction of cleavage; exceedingly thin sheets or flakes can be split off parallel to the base of the flat hexagonal-sectioned prisms in which mica crystals frequently occur; mica, therefore, is said to have a perfect *basal* cleavage. The degree of cleavability of the material on opposite sides of a cleavage plane varies greatly; it may be difficult or simple to split different minerals along the same cleavage direction. Similarly, if a mineral possesses two cleavage directions, it is possible one may be more separable than the other. This *cleavability* is spoken of as

highly perfect (in mica, calcite, etc.),
perfect (in felspar, pyroxene, etc.),
distinct (in olivine, and other minerals), and
imperfect or *difficult* (in corundum, analcite, etc.).

(*d*) FRACTURE.—The term fracture is used to define the kind of surface which is obtained on breaking a crystalline mineral in a direction other than that of the cleavage, if such exists. If the cleavage of a mineral is well developed, as in calcite, it is difficult to obtain a fracture surface; the mineral will break up in cleavage fragments. Quartz, garnet, and several other minerals have practically no cleavage, and consequently only break by fracture. An amorphous body (restricting ourselves to minerals) has no cleavage, and is only liable to fracture. The common types of fracture are: *conchoidal*, with curved, shell-like surfaces; *even*, when the surface, although rough, approximates to a plane; *uneven*, when the surface is rough and irregular; and *hackly*, when there are sharp, jagged elevations.

Cleavage planes are directions of weak cohesion in a mineral. A hard, brittle mineral, like felspar, with two highly-developed cleavages, will readily break up, even under comparatively gentle impact, into angular fragments; whereas quartz, a mineral of similar hardness, but devoid of cleavage, will merely become rounded by such treatment.

(*e*) HARDNESS.—The hardness of a mineral is measured by its resistance to abrasion, and is usually determined by scratching a smooth surface of the mineral. If a mineral can, but with difficulty, be scratched with an ordinary steel knife and can itself scratch window glass, it will have an approximate hardness of 7 on the accompanying relative scale of hardness, where

Common foliated talc	=1
Gypsum or rock-salt	=2
Transparent calcite (Iceland spar)	=3
Crystallised fluorspar	=4
Apatite	=5
Cleaved orthoclase felspar	=6
Quartz (rock crystal)	=7
Topaz	=8
Fresh cleavable corundum	=9
Diamond	=10

The hard minerals, those with a hardness exceeding 6, are most frequently oxides and silicates of aluminium; among these the heavier minerals (with greater specific gravity) are usually harder than the others, the greater density evidently signifying a closer molecular packing of aggregation. In contrast to these aluminium silicates, the heavy metals, gold, lead, etc., are soft; they possess, however, certain properties, malleability, etc., which are absent in the minerals which have been discussed.

(*f*) TENACITY.—Hardness and tenacity are physical properties which appear to be determined by the elasticity and cohesion which exist between the molecules of a crystal. The tenacity or strength

which holds the molecules together varies greatly and induces the following properties, for which certain minerals are noted. Minerals are said to be *brittle*, when they powder readily under attrition (calcite, felspar, etc.); *sectile*, when they can be cut as well as powdered (gypsum); *malleable*, when they can be cut and beaten flat (the metals alone have this property); *flexible*, when they can be bent but remain bent if not forcibly straightened (talc); *elastic*, when they are capable of recovering their shape if distorted within certain limits (mica).

(*g*) SOLUBILITY.—A considerable amount of work has been done in determining the relative solubility of various minerals—particularly in carbonated waters. The subject considerably affects the problem of the decomposition of rocks, and comes under the head of Chemical Denudation. R. Muller experimentally ascertained that carbonated water extracted (in 7 weeks) the following percentages from the undermentioned minerals:

Mineral	Percentage of totals in mineral								% total of weight taken
	SiO_2	Al_2O_3	K_2O	Na_2O	MgO	CaO	P_2O_5	FeO	
Adularia ...	0.1552	0.1368	1.3527	—	—	—	—	trace	0.328
Oligoclase ...	0.237	9.1713	—	2.367	—	3.213	—	trace	0.533
Hornblende ...	0.419	trace	trace	—	—	8.528	—	4.829	1.536
Apatite ...	—	—	—	—	—	1.946	2.12	trace	1.976
Olivine ...	0.873	trace	—	—	1.291	—	—	8.733	2.111

On a previous page it was shown that a mineral substance may be present in more than one condition—crystalline or amorphous. The solubility of the substance will generally be very different in each condition, *e.g.* quartz is practically insoluble except in alkaline water, while opal is distinctly soluble. There are greater differences in the solubility of different minerals in a common solvent, *e.g.* calcite (calcium carbonate) is easily soluble under certain conditions, whereas magnesite (magnesium carbonate) is far less soluble when exposed to the same solvent. The question of solubility is often of considerable importance, as noted in the case of limestones in connection with reservoir sites and the location of dams. It has to be carefully investigated also in connection with the choice of rock for building purposes in a manufacturing region. Chemical works particularly, by the acid fumes emitted into the air, cause a serious disfigurement of the fine carved facings of beautiful buildings. The Houses of Parliament, in Westminster, have had to be carefully examined, and the exposed stone surface elaborately treated, in order to preserve the masonry against corrosion from the acid present in the London air. York Minster is built of the same stone, *i.e.* magnesium limestone (Permian Age),

but in this case the stone has not suffered severely in its exposed surfaces. Much depends on the judicious selection of the stone and method of laying it.

Portland Stone (oolitic limestone) was used for the construction of the Monument which marks the limit of the Great Fire of London in 1666. St. Paul's Cathedral is also largely built of Portland Stone. In both these cases the limestone appears to have resisted very well corrosion by London rain.

The rapid oxidation of marcasite (iron sulphide) has already been referred to. This mineral, on being oxidised, produces ugly brown patches on the surface of the exposed stone. In choosing stone, the presence of and subsequent alteration of such minerals should be carefully borne in mind. Gypsum and a few other comparatively rare minerals also undergo rapid decomposition on exposure, and their presence should be sufficient reason for avoiding the use of the material in which they occur. In some of the new buildings of Imperial Delhi, an efflorescence, traceable to the brickwork backing, has made its appearance on the exposed stone surface of the shaded walls.

(*b*) TEMPERATURE CHANGES.—The surface peeling which is often noticeable on some stone buildings which are exposed to the fierce heat of the sun in the day, followed by sharp frosts at night, is generally due to the strain produced by the unequal expansion of the component minerals in the rock. The cubical expansion of a number of the more important rock-forming minerals has been determined (see Merrill, "Stones for Building and Decoration," 1903, p. 434).

The following co-efficients of cubical expansion * are of interest:

Quartz	0.000036
Orthoclase felspar	0.000017
Adularia felspar	0.000018
Hornblende	0.000028
Tourmaline	0.000022
Garnet	0.000025
Beryl	0.000001
Calcite	0.000020
Dolomite	0.000035

The co-efficients of thermal expansion of plagioclase, augite, diopside, and olivine are not available; they probably have the following approximate values: *i.e.* 0.000022, 0.000030, 0.000032 and 0.000036 respectively.

The *relative* values of the co-efficients of cubical expansion of the various minerals are important. A rock like granite, consisting largely of quartz and orthoclase, must be subject to considerable strain when exposed to great heat and then suddenly cooled. Simi-

* See Tables at foot of opposite page.

larly, a dolomitic marble, composed of equal proportions of calcite and dolomite, or a dolerite with plagioclase felspar and augite, will certainly fracture if heated and then suddenly chilled. A diorite or epidiorite, with hornblende and plagioclase felspar, would be more resistant; and a sandstone (quartzite) of compact texture might have considerable linear expansion.

FUSIBILITY.—Although fire tests are generally confined in metallurgical assays to metallic minerals, they are frequently applied to

EXPANSION WITH HEAT.

Mean co-efficients (between 0° & 100° C., or 32° & 212°F.)

Substance	Cubical Expansion		Linear Expn. at 100° C., if 1 at 0°
	Per°Cent.	Per°Fahr.	
Invar (Special Alloy) ...	.0	.0	1.0
Porcelain	.0000108	.0000060	1.00036
Wood	.0000149	.0000083	1.00046
Granite	.0000236	.0000131	1.00078
Glass	.0000258	.0000143	1.00086
Platinum	.0000266	.0000148	1.00088
Iron (cast)	.0000332	.0000185	1.00111
Iron (wrought)	.0000355	.0000197	1.00122
Steel (mild)	.0000363	.0000201	1.00111
Antimony	.0000373	.0000207	1.00124
Steel (hard)	.0000375	.0000208	1.00127
Nickel	.0000375	.0000208	1.00127
Bismuth	.0000417	.0000232	1.00139
Gold	.0000443	.0000246	1.00148
Copper	.0000515	.0000286	1.00172
Brass	.0000565	.0000314	1.00188
Silver	.0000574	.0000319	1.00191
Tin	.0000657	.0000365	1.00219
Aluminium	.0000667	.0000370	1.00222
Lead	.0000839	.0000466	1.00279
Zinc	.0000883	.0000491	1.00294
Mercury	.0001815	.0001008	1.00605
Vulcanite	.0002273	.0001263	1.00758
Glycerine	.0002520	.0001400	1.00840
Water	.0004386	.0002431	1.0146
All Gases	.003663	.0020305	1.1221

The co-efficients of linear expansion are one third those of cubical expansion.

CONDUCTIVITY OF METALS.

Substance	Heat Cond.	Electrical Cond.
Silver	100.0	100.0
Copper	73.6	73.3
Gold	53.2	58.5
Aluminium	31.3	60.5
Brass	23.6	21.5
Zinc	19.9	29.0
Tin	14.5	22.6
Iron	11.9	13.0
Lead	8.5	10.7
Platinum	6.4	10.3
Bismuth	1.8	1.9
Mercury	1.5	1.6

other minerals with a view to noting the flame colouration produced, and for observing the change of colour, exfoliation, intumescence, and fusibility of a mineral. The determination of the fusibility of a mineral is often a valuable guide in the identification of the mineral. The scale of fusibility given below is often used for reference in such tests (taken from "Elements of Optical Mineralogy," A. N. Winchel, 1922).

Order	Mineral	Approx. Fusing point in °C.	Remarks
1	Stibnite	525°	Fuses easily in a candle flame.
2	Chalcopyrite	800°	Fuses slowly in a gas flame.
3	Almandine (garnet)	1050°	Only finest splinters rounded in a gas flame.
4	Actinolite	1200°	Standard size fragments are rounded easily before the blow pipe.
5	Orthoclase	1300°	Standard size fragments are rounded with difficulty before the blow pipe.
6	Bronzite	1400°	Only finest splinters rounded on points with difficulty before the blow pipe.
7	Quartz	above 1400°	Infusible before the blow pipe.

Fusibility according to Brun :

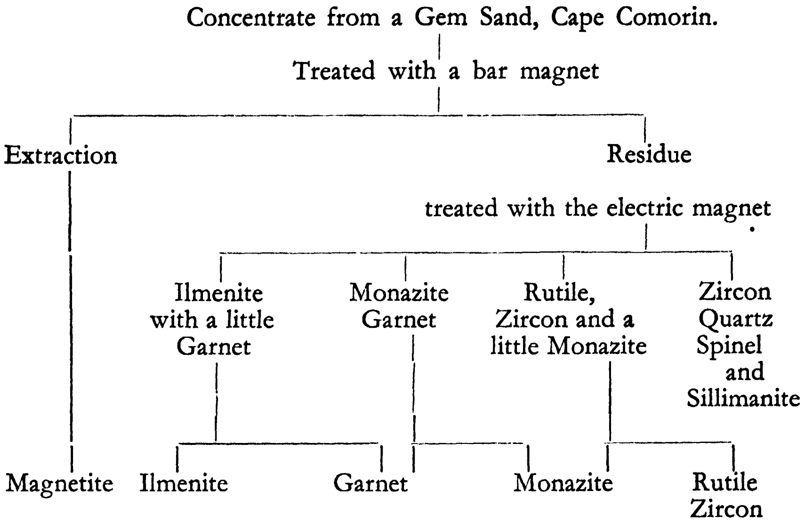
Hornblende	fuses	at from	1,060° to 1,070° C.
Tremolite	,,	at	1,270° C.
Magnetite	,,	at from	1,190° to 1,225° C. (Dvelter).
Augite	,,	at	1,230° C.
Nephelite	,,	at	1,270° C.
Labradorite	,,	at	1,370° C.
Anorthite	,,	at from	1,490° to 1,520° C.
Olivine	,,	at	1,750° C.
Quartz	,,	at	1,780° C.

MAGNETIC PROPERTY.—Recent experimental work has shown that several minerals which contain appreciable amounts of iron in their composition are susceptible to the influence of a magnetic field. It has been found possible, by suitably varying the strength of the magnetic field, to separate the more magnetic from the less magnetic, and the less magnetic from the non-magnetic minerals in a dried sample of mineral sand. Some minerals contain varying amounts of iron, and in these varieties those with the greater percentage of iron are more susceptible to magnetic influences than those with less. The magnetic properties of the common rock-forming minerals are given below :

	Steel taken as	100,000
	Magnetite taken as	64,000
Highly Magnetic	Titanoferrite	48,000
	Ilmenite (some kinds)	20,000 to 12,000
	Pyrrhotite	4,700 to 2,600
	Ilmenite (normal)	?
	Biotite (iron rich)	?
	Pyroxene (iron rich)	?
Moderately Magnetic	Amphibole (iron rich)	?
	Garnet (almandine, etc.) ..	300 to 100
	Olivine	250 to 60
	Hypersthene	140
	Chromite	140
	Augite (normal)..	106 to 71
	Biotite (normal)..	?
	Tourmaline	?
Weakly Magnetic	Staurolite	77
	Pyrite	60
	Hornblende	57 to 26
	Monazite..	?
	Epidote	49
	Hematite..	43
	Limonite..	22
	Actinolite	14
Practically Non-magnetic	Kyanite	12
	Chlorite	10
	Sillimanite	—
	Muscovite	—
	Tremolite	trace
	Apatite	—
	Quartz	—
	Felspars	—
	Calcite	—
	Dolomite	—
	Gypsum	—
	Spinel	—

This subject has been fully discussed by A. Holmes in his book "Petrographic Methods and Calculations," 1921 (Murby). On page 96 of the above this investigator says: "In separating sand concentrates, the magnetic method is of unrivalled utility."

The following example shows the steps taken in a particular case :



ELECTRICAL CONDUCTIVITY.—T. Crook, in " The Mining Magazine " (Vols. XV, 1909, p. 260 ; and XVI, 1911, p. 109) described a method of determining the relative conductivity of various minerals, and showed how it was possible to affect a separation of different types by means of electrostatic attraction. A thoroughly dried mixture of mineral grains is placed on a copper plate, and a negatively charged rod of sealing wax is brought near the grains. By so doing, the induced charges on the grains of good conductivity result in these grains leaping to the electrified rod. With the help of a simple piece of apparatus based on the principle of the electrophorous, the following determinations * were made :

Good Conductors (Easily attracted)	Moderate Conductors	Bad Conductors (not attracted)
Magnetite		Calcite
Titanoferrite	Other titanium	Dolomite
Ilmenite	Minerals	Gypsum
Hematite	Pyroxenes and	Quartz
Pyrite	Amphiboles	all other silicates and
Pyrrhotite	rich in iron	alumino-silicates.
Chromite	Tourmaline	Spinel
and other related	Biotite	Corundum
Spinels		Apatite

* See Petrographic Methods, Holmes, 1921, p. 96 for further particulars.

CLASSIFICATION OF MINERALS.—In the accompanying table, showing the physical characters of the common rock-forming minerals, the classification laid down by Dana has been adopted. Eight classes are instituted, and each has been subdivided for convenience of study. Except for quartz, in Class V under Oxides, it is seen that most of the rock-forming minerals belong to Class VI, Oxygen Salts, and chiefly to the group designated as Silicates. Detailed information on the crystal forms, optical properties, etc., of these minerals will be found in most text books on mineralogy.

DETERMINATION OF MINERALS.—An experienced mineralogist can frequently identify by a glance many a mineral. In a small fraction of time he has noticed the colour, lustre, presence or absence of cleavage and, possibly, the heaviness. If the mineral occurs in crystals, or shows several facets, this will help in the recognition of the mineral. However, even in experienced hands it is always safer to subject a specimen to a few determinative tests, *e.g.* specific gravity, hardness, streak, brittleness, fracture, etc. These tests are minutely described in most text books of determinative mineralogy, such as " A Text Book of Mineralogy " by E. S. Dana.

SPECIFIC GRAVITY.—If moderately large specimens of the pure mineral are available, the specific gravity is determined in the usual way on a balance, by weighing in air (W) and then in water (w) and making the calculation Sp. Gr. $= \frac{W}{W - w}$. Should it be possible to procure only small grains of the substance (pure), the specific gravity can be readily ascertained by dropping the particles into heavy liquids of known density and noting the liquid in which the grains remain suspended. These heavy liquids have been found very useful in separating different minerals from a powdered mixture or sand. The liquids most frequently used are Sonstadt's (Thoulet's) solution of potassium (very poisonous) mercuric iodide, which has a maximum specific gravity of 3.196, but can be diluted in any proportion with water; Klein's solution (cadmium borotungstate), which has a maximum specific gravity of 3.6, and can also be mixed in any proportion with water; and methylene iodide, maximum specific gravity 3.3243 at 16° C., which can only be diluted with benzol. The test solutions can be made up by using minerals of known specific gravity as " sinkers."

HARDNESS.—The relative hardness of a mineral is estimated by scratching it with, or on, substances of known hardness. The degree of hardness is usually referred to Moh's scale (given on p. 24). Thus, if a mineral scratches orthoclase felspar easily, but is only just able to scratch quartz, its hardness will be about 7. Occasionally a deceptive

determination is possible. This is usually the case with brittle friable substances, owing to the loose grains being rubbed out and the mineral appearing softer than it really is. In some cases a mineral shows differences in hardness in different directions: kyanite, for example, when in bladed crystals, has a hardness of 5 lengthwise and of 7 across the crystal blades.

STREAK.—When a mineral is rubbed across the hard matte surface of a porcelain plate, some particles of it are left on the plate—the colour of this streak has been found very useful in determining some dark metallic minerals.

MAGNETIC PROPERTY.—If after testing the mineral in magnetic fields of different intensity and noting the magnetic susceptibility of the mineral, its identity is still in doubt, the accompanying fire tests are often carried out.

EFFECTS OF HEAT.—Simple heating of the mineral frequently leads to its decrepitation, exfoliation, or change of colour. Stronger heating results in ignition or fusion, and the relative fusibility of the mineral is often a valuable guide in ascertaining its identity. In the process of heating, any colouration of the flame caused by the mineral will give a clue to the presence of certain elements in the composition of the mineral.

CHEMICAL TESTS.—Should the above manipulations not lead to the recognition of the mineral, it will be interesting to perform the usual chemical tests. These consist in noting the action of various acids (*e.g.* hydrochloric, hydro-fluoric, etc.), and the effects of etching and staining with suitable solutions.

OPTICAL TESTS.—In the event of the previous tests having stimulated the engineer into verifying his determinations by examining the optical properties of the mineral, he is advised to make himself familiar with the structure of crystals. The most frequent optical tests are those of refractive index and pleochroism; when, for example, the mineral to be examined is a gemstone with crystal faces or facets, the simplest method of determining its refractive index is to examine it with a Herbert Smith Refractometer. This simple and comparatively inexpensive apparatus, although suitable for all common rock-forming minerals, is limited to measurements up to 1.79, and is consequently unable to determine the refractive indices of colourless zircon and diamond. The pleochroism is ascertained by means of an equally simple instrument known as the dichroiscope or Haidinger's prism. If, however, the subject of determinative petrology is being taken up enthusiastically, perhaps the engineer would be best advised to get a petrological microscope; with such an instrument he will be able to determine the refractive index, pleochroism, etc., of the mineral grains

composing a powder. Further, he will be equipped for the microscopic examination of thin slices of rock. It is not to be forgotten, however, that a microscope carries with it a number of accessories, such as section-cutting apparatus; boxes containing bottles of liquids of known refractive index; sections of common rocks and various minerals for reference, etc. These adjuncts are often of great value, and facilitate the work of determination to such an extent that it may be possible to eliminate all the physical tests previously outlined, or at least those which involve the purchase of expensive apparatus and fittings. For example, a very convenient method of determining the refractive index of very small crystals or crystal grains can be employed with the microscope in the following way. A few grains are placed on a thin glass plate (slide) and a cover placed over them. A drop of liquid of known refractive index is then put at the edge of the cover glass, so that it is drawn in among the mineral grains by capillary action. Now, if the slide is examined under the microscope, the mineral grains will either show up weakly or strongly in the liquid which surrounds them. There is usually a thin streak of light along the margins of the mineral grains—this light band will appear to move laterally when the microscope tube is slightly raised. The rule is that the "Becke line" (the light band) moves towards the mineral of higher refractive index when the microscope tube is lifted higher. Thus it is seen, by repeating the test with other liquids from the graduated set, that the refractive index of the mineral can be fairly accurately determined.

The following liquids have been found to answer very well for determinations of refractive index:

	Refractive Index.
Water	1.334
Petroleum	1.450
Lavender oil	1.460
Olive oil	1.469
Turpentine	1.472
Castor oil	1.481
Benzol	1.498
Xylol	1.500
Sandalwood oil	1.507
Cedarwood oil	1.516
Monochlor-benzol	1.526
Canada balsam	1.534
Cinnamon oil	1.535
Clove oil	1.540
Monobrom-benzol	1.561
Cassia oil	1.600
Aniseed oil	1.546
Carbon bisulphate	1.628

	Refractive Index.
Monochlor-naphthalene	1.635
Monobrom-naphthalene	1.655
Klein's solution	1.700
Sonstadt's (Thoulet's) solution ..	1.716
Methylene iodide	1.750

Some investigators prefer to make up a set of solutions of potassium mercuric iodide (Sonstadt's or Thoulet's solution) both for determinations of specific gravity by heavy liquid separation and for measurements of refractive index. Weinschenk and Clark (see " Petrographic Methods," 1912, p. 37) give the following data for various solutions of this fluid :

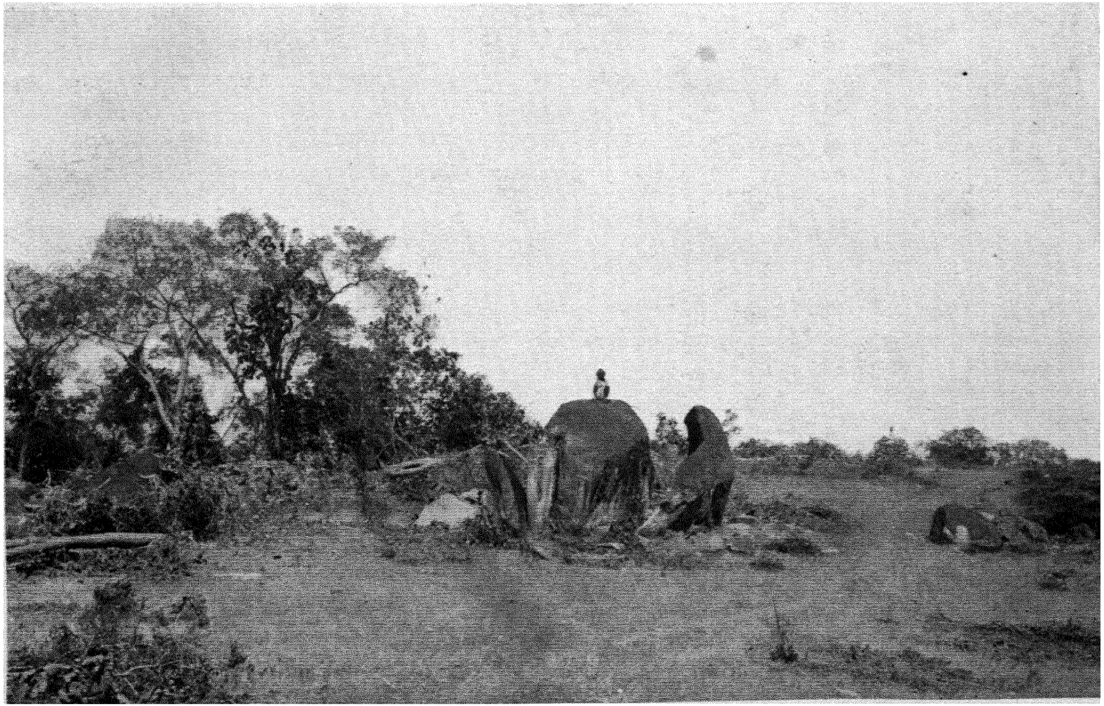
Specific Gravity.	Refractive Index.
3.2	1.730
3.1	1.715
3.0	1.696
2.9	1.677
2.8	1.658
2.7	1.640
2.6	1.620
2.5	1.602
2.4	1.583
2.3	1.565
2.2	1.546
2.1	1.527
2.0	1.509
1.9	1.491
1.8	1.473
1.7	1.455
1.6	1.437
1.5	1.419

EXAMPLES.

(1) To take an interesting example : some beautiful claret-coloured crystals are brought in and are thought to be rubies. On close examination they are seen to resemble rhombic dodecahedra. This, if correct, groups them in the cubic system, whereas the ruby is in the hexagonal crystal system. The specific gravity, determined by the sp. gr. balance, is found to be 3.9—about the same as the ruby. The hardness is the same as quartz, *i.e.* 7, the ruby being 9. It is obviously not a ruby ; and cannot be a spinel, because the hardness of red spinel is the same as topaz, *i.e.* 8. The refractive index is not very much greater than methylene iodide. Looking up the tables, we conclude that the mineral is the variety of garnet known as almandine. This is confirmed by proving the mineral to belong to the cubic crystal system.

(2) To take another example. We have a sample of dark river sand. On passing a horse-shoe magnet over it, more than half turns

PHOTOGRAPH III.



Per favour D. G. S. I.] A "SUN-SPLIT" GNEISSIC BLOCK. [*Photo by H. Walker.*

The expansion produced in the gneissic block by the sun's heat, and the subsequent rapid cooling at night, has ultimately led to the cracking and splitting of the block.

SUN-SPLIT BLOCK OF GNEISS, BETUL DISTRICT, INDIA.

[*To face page* 34.

out to be magnetic. The remainder is cream-coloured, but on close examination is seen to consist of two kinds of minerals: one is in rounded grains, evidently water worn, and the other is in doubly-pointed stout little prisms with comparatively sharp edges. It is obvious that this prismatic mineral is very hard. Both scratch glass and orthoclase felspar, *i.e.* they have a hardness greater than 6. The prismatic mineral with some difficulty scratches the other and also quartz, *i.e.* its hardness is greater than 7. The softer mineral floats in Thoulet's solution (sp. gr. 2.8), while the other sinks in Thoulet's solution, of sp. gr. 3.20. The first mineral has a refractive index of above clove oil (1.54) and less than cinnamon oil (1.56), and is about 1.546 according to Thoulet's solution; the other mineral has a refractive index far above methylene iodide (1.75). We suspect the first to be quartz and the other to be colourless zircon.

CHAPTER III

PRINCIPAL ROCK TYPES

ALTHOUGH a rock may be defined as an aggregate of minerals, the term is more specifically applied to those mineral aggregates which form an essential part of the earth's crust. It is necessary in this sense that all rocks must possess certain individual characteristics by which they can be easily recognised. Numerous mineral aggregates, such as the various metalliferous ores, etc., although important from a metallurgical or economic point of view, constitute a very insignificant part of the rocky portion of the globe; they are, therefore, strictly speaking, not rocks. In other cases it is more difficult to decide. As a rule, however, it is undesirable to elaborate the subdivisions of the chief rock groups.

There are three great classes into which it is usual to group the various types of rock which have been recognised on the crust of the earth:

(1) Igneous rocks, or those which have solidified from a molten condition;
(2) Sedimentary rocks, or those which have derived their material from pre-existing rocks; and
(3) Metamorphic rocks, *i.e.* those which, as their name indicates, are changed or modified varieties of the preceding classes.

Each of these great classes is again capable of much subdivision into families, etc., depending on their mode of occurrence and chemical or mineralogical composition, as shown in the accompanying table of classification (see folding plate).

CLASSIFICATION OF ROCKS.—The arrangement of vertical and horizontal divisions shown on the accompanying scheme of classification (see folding plate) is intended to represent portions of a section of the earth's crust. The top horizontal set of divisions, 1 to 20, are supposed to be part of the earth's surface. On the extreme left, divisions 1 to 5, there is an imaginary mountain range in which only igneous rocks occur. In the middle, divisions 6 to 14, there are supposed to be deposits of sedimentary material which have been laid

down by eastward (to the right) flowing streams which drain the hypothetical mountain tract. The coarse debris naturally accumulates near the mountains, whilst the fine suspended mud and the soluble constituents are swept into the sea. On the extreme right, divisions 15 to 20, there are important surface accumulations.

The successive divisions, downwards, A, B, C, D, E, and F, represent zones—one below the other—from the surface into the depths of the earth; thus:

Zone A is the surface of the ground on which deposition takes place.

Zone B includes all rocks which have been formed at the surface, such as ash beds, lava flows, soft sandstones, etc., and are actually exposed at the surface of the earth or lie above the level of the stationary ground water.

Zone C extends from near the surface to a considerable depth. In it the rocks, although subject to heavy earth pressure, are not exposed to high temperatures; unconsolidated beds are more or less consolidated, and the whole zone is probably below the level of the stationary ground water. Dikes and sills and lacoliths of the igneous rocks occur in this zone in intrusive relationship with older rocks.

Zone D is at a great depth from the surface. No open fissures can exist at this depth, because the pressure is sufficient to cause even the hardest rocks to "flow." The temperature range in this zone, although possibly above 365° C., the critical temperature of water, does not extend to the melting-point of the rocks. Great masses of granite and other igneous rocks are associated with this zone. The sedimentary rocks become thoroughly consolidated under the enormous pressure to which they are subjected at this depth.

Zone E represents the dynamic aspect of Zone D. Both are at approximately the same depth. When no earth-movements are operative, the conditions of Zone D exist; but when immense tectonic forces—of compression and torsion and shear—act on the somewhat pliable rock, distortion takes place. Igneous rocks, like granites, etc., are rendered gneissose; schistosity is developed; sedimentary rocks are converted into their metamorphic equivalents, and quartzites, phyllites, marbles, etc., are formed.

Zone F.—Zones D and E pass downward into a zone subject to enormous pressures and very high temperatures. The rocks are thought to be in a semi-plastic condition. When merely static pressures prevail, the rocks crystallise with coarse granitic textures.

Zone G is considered to be an extreme condition of Zone F. The prevailing pressure and temperature is presumed to be so high that a release of pressure in any part of this zone immediately results

in a liquefaction of the plastic rocks in that region. This zone constitutes the petrological melting-pot for all rocks. Dr. Fermor has designated it the infra-plutonic zone.

A careful examination of the classification will enable most people to trace the history and mode of formation of the commoner types of rock met with in engineering operations.

RELATIVE PROPORTIONS OF VARIOUS ROCKS.—It is impossible to estimate the proportions of the various types of rock. Various approximations have been made, and these results are summarised in the table below :

Igneous rocks	A. Acid types	63 %	95 %	These include their
	B. Basic types	32 %		
Sedimentary rocks	C. Shales	4 %		metamorphic
	D. Sandstones	0.75 %		
	E. Limestones	0.25 %	5 %	representations.

(N.B.—See chemical analyses below.)

It is seen from this analysis how large a part of the earth's surface consists of acid igneous rocks, the total proportion of all the igneous rocks being no less than 95 per cent. of the whole.

CHEMICAL COMPOSITION.—Dr. F. W. Clarke ("Data of Geo-Chemistry, Bull. No. 330, U.S. Geological Survey, p. 261) estimates the chemical composition of these various types of rock as being :

	A and B	C	D	E	Av rage of whole.
Silica	59.87	58.10	78.33	5.19	59.79
Alumina	15.02	15.04	4.77	0.81	14.92
Ferric oxide	2.58	4.02	1.07	0.54	2.63
Ferrous oxide ..	3.40	2.45	0.30	—	3.33
Magnesia	4.06	2.44	1.16	7.89	3.98
Lime	4.79	3.11	5.50	42.57	4.82
Soda	3.39	1.30	0.45	0.05	3.28
Potash	2.93	3.24	1.31	0.33	2.96
Water	1.86	5.00	1.63	0.77	1.98
Titanium oxide ..	0.72	0.65	0.25	0.06	0.71
Zirconium oxide ..	0.03	—	—	—	0.03
Carbon dioxide ..	0.52	2.63	5.03	41.54	0.74
Phosphorous pentoxide	0.26	0.17	0.08	0.04	0.25
Sulphur	0.11	—	—	0.09	0.10
Chlorine	0.42	1.49	0.12	0.12	0.44
Total With other constituents	100.00	100.00	100.00	100.00	100.00

An average chemical analysis of the various groups of the igneous rocks is shown below. These values do not give any idea of the great variations in composition which are frequently found in certain types of each of the groups.

	1	2	3	4	5
Silica	71.0	62.0	58.0	47.0	40.0
Alumina	15.0	20.0	18.0	16.0	6.0
Ferric oxide	1.0	1.0	2.7	3.0	5.0
Ferrous ,,	1.0	1.7	3.8	8.0	8.0
Magnesia	0.7	0.8	2.5	8.5	32.0
Lime	1.4	1.6	5.8	12.0	6.0
Soda	3.5	5.3	3.7	2.0	0.5
Potash	5.0	5.0	2.5	0.8	0.5
Other constituents	1.4	2.6	3.0	2.7	2.0
Total	100	100	100	100	100

(1) Acid group.
(2) Acid intermediate group.
(3) Basic intermediate group.
(4) Basic group.
(5) Ultra-Basic group.

Details of the composition of the sedimentary rocks are given in the previous table. The composition of the metamorphic rocks (except certain peculiar residual types such as laterite, or special varieties such as coal) are similar to the rocks—igneous or sedimentary —which have been metamorphosed.

MINERAL COMPOSITION.—Rough guesses, based on some determinative work, have been made regarding the importance and relative proportions (by weight) of the minerals which compose the rocks of the earth's crust.* The most recent of these (" Economic Aspects of Geology," by C. K. Leith) gives the following percentages :

	Per cent.
(1) Felspars	49
(2) Quartz	21
(3) Augite, hornblende and olivine	15
(4) Mica	8
(5) Magnetite	3
(6) Titanite and ilmenite	1
(7) Kaolin, limonite, dolomite, hematite, calcite gypsum, etc.	3
	100

* See footnote on page 40.

The same authority estimates the following percentages of various minerals in the igneous rocks :

	Per cent.
(1) Felspar	50
(2) Quartz	21
(3) Augite, hornblende and olivine	17
(4) Mica	8
(5) Magnetite	3
(6) Titanite	1
	100

And the following percentages of various minerals in the sedimentary rocks :

	Per cent.
(1) Quartz	35
(2) Felspar	16
(3) White mica	15
(4) Kaolin	9
(5) Dolomite	9
(6) Chlorite	5
(7) Calcite	4
(8) Limonite	4
(9) Gypsum, carbon, apatite, rutile, magnetite, zircon, etc.	3
	100

IGNEOUS ROCKS.—The igneous rocks (see Divisions 1 to 5 in the accompanying classification) are usually subdivided into several groups or families : (1) The Acid group, or Granite-rhyolite family ; (2) the Acid intermediate group, or Syenite-trachyte family ; (3) the Basic intermediate group or Diorite-andesite family ; (4) the Basic group, or the Dolerite family ; and (5) the Ultra-Basic group, or Peridotite, etc., family. This arrangement depends largely on the composition of the rocks, *i.e.* the relative quantities of acid (silica, etc.) and basic constituents (iron, magnesium, etc.) which they contain. These groups are next classified as Volcanic, Hypabysal and Plutonic varieties, according to their superficial or deep-seated origin. The acid varieties generally contain pale-coloured minerals, quartz and

* By combining a large number of analyses of rocks of all sorts, F. W. Clarke has estimated the relative amounts of elements in the crust of the earth :—

	Per cent		Per cent		Per cent.
Oxygen	47.02	Titanium ...	.41	Chromium ...	.01
Silicon	28.06	Hydrogen ...	.17	Nickel	.01
Aluminium ...	8.16	Carbon	.12	Lithium ...	.01
Iron	4.64	Phosphorus ...	.09	Chlorine ...	.01
Calcium	3.50	Manganese ...	.07	Flouorine ...	.01
Magnesium ...	2.62	Sulphur ...	.07		
Sodium	2.63	Barium ...	.05		100
Potassium ...	2.32	Strontium ...	.02		

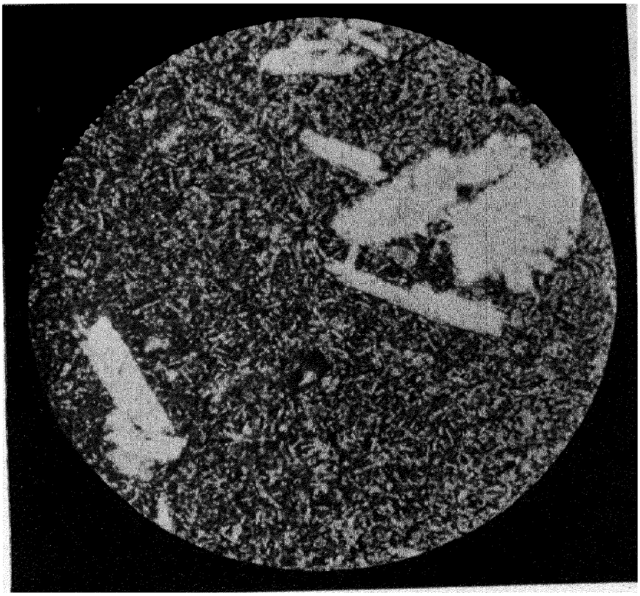


PHOTO-MICROGRAPH I.

Fine grained porphyritic basalt.

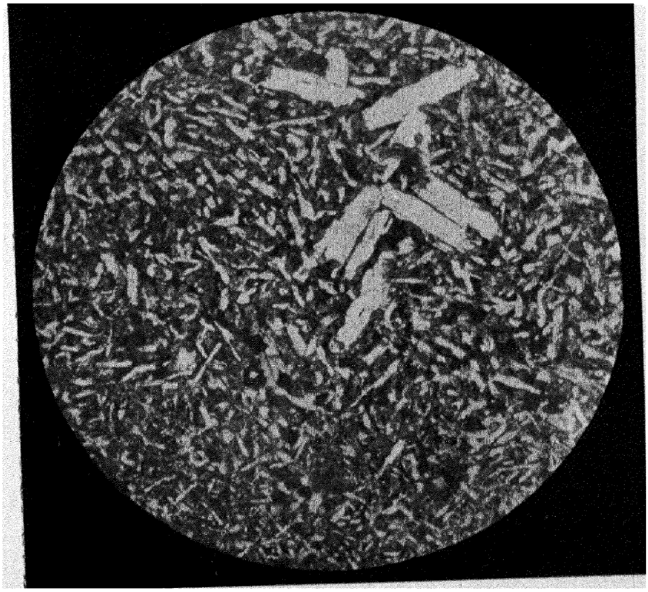


PHOTO-MICROGRAPH 2.

Porphyritic basalt.

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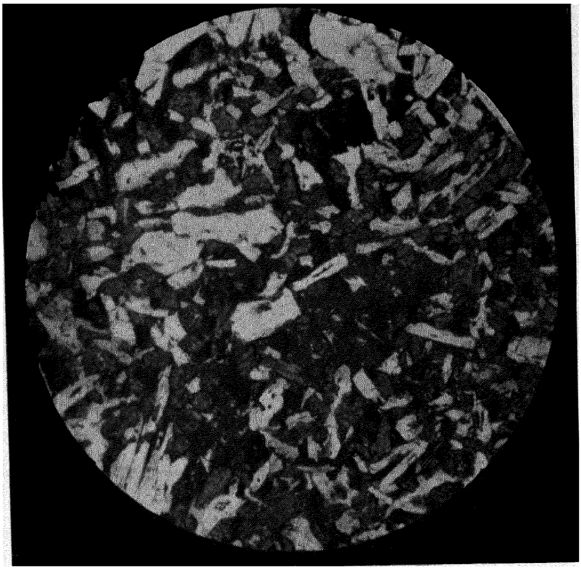

PHOTO-MICROGRAPH 3.

Typical doleritic basalt.

PHOTO-MICROGRAPH 4.

Dolerite.

[To face page 41.

felspar, and are consequently pale-coloured in appearance. The basic varieties contain large amounts of augite, hornblende, olivine, etc., frequently with—but sometimes without—felspar, and are dark in colour. All the plutonic, and most of the hypabysal types consist entirely of interlocked or interlaced crystals. They are wholly (or holo-) crystalline. With respect to the size of the crystal grains in wholly (holo-) crystalline rocks, the designations coarse, medium, fine, and micro-crystalline are applied. These terms explain themselves. Some hypabysal and many volcanic rocks contain a matrix of volcanic glass with large individual crystals. They are said to have a porphyritic texture. Among the volcanic rocks greater differences exist. Certain kinds contain steam holes or vesicles (vesicular), others have the porous texture of pumice, while some varieties are fragmental, such as volcanic ash, and others are wholly of volcanic glass, *e.g.* obsidian (acid-rhyolitic-glass) and tachylite (basic-basaltic-glass).

Except for the vesicular and fragmental types, most igneous rocks when undecomposed have an impervious texture and do not usually absorb water. Their water-containing capacity normally depends on the cracks and joints which traverse these rocks.

TEXTURE (*Granular*, *Porphyritic* and *Ophitic*).—We have already discussed the terms coarse, medium, fine, and micro-crystalline with regard to the size of the mineral grains in holo-crystalline rocks. For igneous rocks in general it is convenient to speak of coarse, medium, and fine grain varieties, whether they are holo-crystalline or not. The types of deep-seated origin are generally coarse-grained, while those which have been chilled may have medium to fine-grained textures. This difference of texture is very well illustrated by the following series of photographs of the microscope sections of a dolerite dike. The specimens were collected from a dike in the Chhindwara District of the Central Provinces of India.

No. 1 was taken from the margin of the dike at its contact with gneisses. The photo-micrograph (magnification 25 times in all these photographs) shows long (phenocrysts), *i.e.* relatively large porphyritic crystals of plagioclase felspar in a ground mass of augite and volcanic glass. As seen, these porphyritic crystals are not truly idiomorphic.

No. 2 was collected 1 foot away from the contact. The same minerals are seen, although the individual grains are larger than in the previous specimen. This rock would make excellent road metal. It is a typical basalt.

No. 3 was obtained 2 feet away from the plane of contact. There is less interstitial volcanic glass and the texture is coarser than in the previous example, and may be classed as medium grained. It would

be suitable for road metal and for paving setts. It has the texture of a doleritic basalt.

No. 4. A sample, collected 5 feet from contact, shows typical dolerite with practically no glassy matter. It is almost holo-crystalline and relatively coarse grained. The felspars show fairly good idiomorphic features. It makes excellent setts and building stone, while the sharp fragments are useful for concrete.

No. 5 (Reg. No. 826). Specimen taken from middle of dike (36 feet from contact) shows coarse, granitoid texture. There is no glassy matter, *i.e.* it is holo-crystalline. Some specks of magnetite are visible between the large interlocked crystals of plagioclase felspar and augite. The felspar outlines are as usual indicative of an earlier crystallization than the augite which forms the matrix. It is coarse dolerite or gabbro. Owing to the great difference in the cubical expansion of plagioclase felspar and augite (see section on rock-forming minerals), this rock would crumble if it were exposed to fire and then drenched with water.

The influence of the shape, size, and mineral composition of the component grains in various rocks will be discussed in a later section. For the present it is enough to say that when crystallization takes place in a solidifying molten or plastic rock mass, certain peculiarities of texture develop. Thus, if two mineral substances crystallise simultaneously, adjacent individuals will frequently hinder each other in such a way that all crystallographic outlines may be suppressed. These irregular outlined crystal grains are said to be *allotriomorphic* or xenomorphic.

Should, however, one mineral crystallise before the other, as in the case of the felspar seen in the Photomicrographs 1 to 5, they will assume crystal shapes and show crystallographic outlines in section (see the Photomicrograph No. 16 of syenite). These crystal grains are *idiomorphic*, or automorphic.

When allotriomorphic grains are equal-sized and interlocked with sharp irregular outlines, as in the case of the texture of many granites, the texture is vaguely said to be *granitoid*. If these interlocked grains have a somewhat rounded shape, the texture is more appropriately said to be *granular*. The rocks which show the true granular texture most frequently are the crystalline limestones, calc-gneisses, and granulites. As these rocks are not generally of igneous origin, it has been felt to be more satisfactory to speak of this granitoid, or granitic, or granular texture as *granulitic* texture when speaking of the equal-sized, allotriomorphic, crystalline grains in a wholly (holo-) crystalline, volcanic rock. Should a holo-crystalline, igneous rock consist of equal-sized grains, say of two minerals, with one mineral

showing idiomorphic features (see Photomicrograph 5), it is convenient to speak of the texture of the rock being *ophitic*. If some of the idiomorphic grains are of much larger size than the other grains, whether these show a granulitic texture or an ophitic texture with regard to each other, then the rock is said to be *porphyritic* in texture —the large idiomorphic individuals being *phenocrysts* or porphyritic crystals. It frequently happens that the intergrowths of small granular crystals of one mineral scattered irregularly without common orientation in a larger crystal of another mineral produce a peculiar spotted lustre when a specimen is examined in reflected light—this lustre mottling is known as *poikilitic* texture, and sometimes as implication texture. These terms are well illustrated and described in "The Fundamental Principles of Petrology," by E. Weinschenk, which has been translated from the German by A. Johannsen.

Amongst the foliated gneissose rocks there is usually a rough parallelism of the mineral particles. This parallelism is frequently disturbed by the presence of " knots " or " eyes " of large individual crystals which have an oval section. When a foliated rock shows this peculiarity in a conspicuous manner, it is said to have an *augen*, eye, texture. Occasionally the foliation is seen to be minutely twisted and contorted.

ACID ROCKS.—Granite, granite porphyry, rhyolite represent the general family with their plutonic, hypabysal, and volcanic types. The granites are usually coarse-grained, though they vary in texture. They generally consist of recognisable grains of quartz, orthoclase felspar, and mica, either white or black, or both. Many varieties occur in which hornblende or other minerals may be present. The granites are, as a rule, pale grey, bluish, or reddish coloured, and give soft shades to buildings made with such material. The following kinds of granite are now well known: the coarse pink porphyritic granite of Dartmoor; the medium-grained greenish Mount Sorrel granite which contains much hornblende; the medium-grained brownish Shap granite with its bold, dark flesh-coloured porphyritic crystals of orthoclase felspar; the medium-grained grey granite of Aberdeen, which contains a white felspar and dark (biotite) mica as characteristic minerals; and the red Peterhead granite, with its reddish pink grains of felspar. The hypabysal forms—*i.e.* porphyry, etc.—are usually porphyritic in texture, though of the same general composition as granite. The volcanic representations—*i.e.* rhyolite, etc.—are either glassy (obsidian) or exceedingly fine-grained (crypto-crystalline) in texture.

The specific gravity of these rocks varies from 2.55 in the fine-textured types (rhyolites) to over 2.65 in granite. They weigh from

155 to nearly 175 lbs. per cubic foot for solid blocks. The crushing strength averages 800 tons per square foot for fine-grained granites, 1,000 tons per square foot for medium-grained types, and 700 tons per square foot for coarse-grained granites.

Granites with much visible quartz, such as the rock of which the Duke of York's column and the steps leading from Waterloo Place to the Mall are built, are particularly liable to disintegration when exposed to abnormal variations of temperature (see section on rock-forming minerals). Granite is said to fuse at about 1,200° C. to 1,300° C., depending on the percentage of silica, but see page 12.

ACID INTERMEDIATE ROCKS.—Syenite, porphyry, trachyte represent the plutonic, hypabysal, and volcanic types of this group of rocks. They have very similar textures to those of the granite family. Quartz is seldom evident in visible grains; subsidiary minerals, on the other hand, are more frequently present, and produce several varieties—hornblende syenite, nepheline syenite, etc. A cubic foot of syenite weighs, roughly, 170 lbs., but the weights of different kinds vary. The specific gravity varies from 2.60 to 2.72 or more. In strength the syenites are generally somewhat superior to granites of similar texture. Like the granites, these rocks can often be quarried in enormous blocks, owing to the great distances between the successive joints. The most readily decomposable mineral in both normal syenites and granites is the orthoclase felspar. This decomposition is easily detected by an examination of a thin section under the microscope. Certain varieties, such as phonolite (clinkstone), are resonant when slabs of it are struck with a hammer. These rather finer-grained types make good paving stone because of their weathering qualities.

BASIC INTERMEDIATE ROCKS.—Diorite, porphyrite, andesite are respectively the deep-seated, hypabysal, and volcanic representatives of this family of rocks. They generally contain appreciable quantities of augite (pyroxene) or hornblende (amphibole), and very rarely show any trace of free grains of quartz (even under the microscope). Plagioclase felspar replaces the orthoclase felspar of the more acid types. The texture varies from granular to porphyritic; the colour—owing to the ferro-magnesian minerals—is usually dark. The compressive strength of some of the medium-textured varieties of diorite is often as much as 1,500 tons per square foot (crushing). The specific gravity of diorite is, roughly, 2.85; and a cubic foot of the rock weighs 175 to 180 lbs. Andesite, on the other hand, may have a specific gravity as low as 2.70; a cubic foot of this rock weighs from 165 to 172 lbs. The various kinds of basic intermediate rocks are tough and durable if the specimens chosen are undecomposed. The

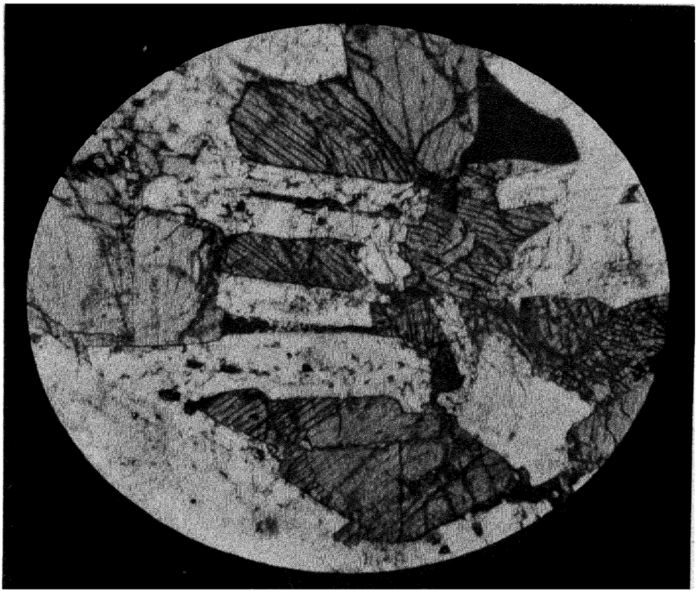

PHOTO-MICROGRAPH 5.

Gabbro.

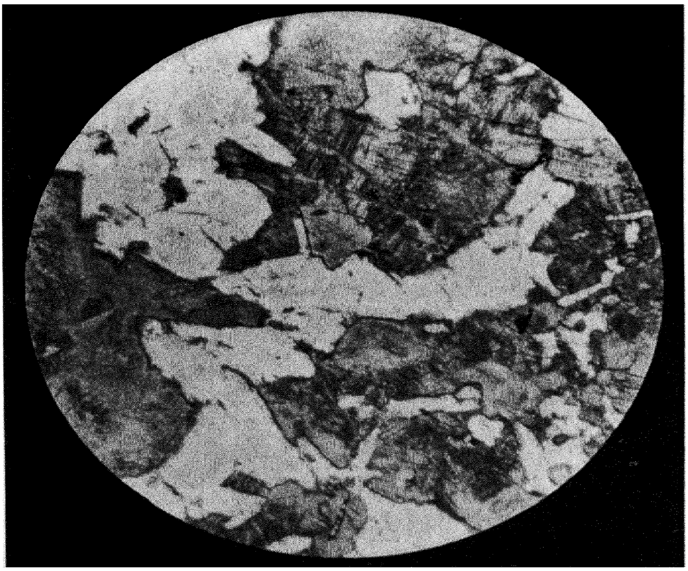

PHOTO-MICROGRAPH 6.

Diabase.

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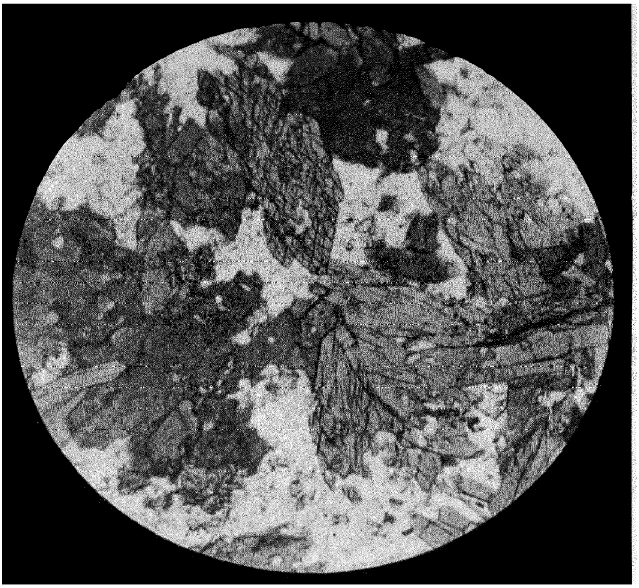

PHOTO-MICROGRAPH 7.

Normal epidiorite.

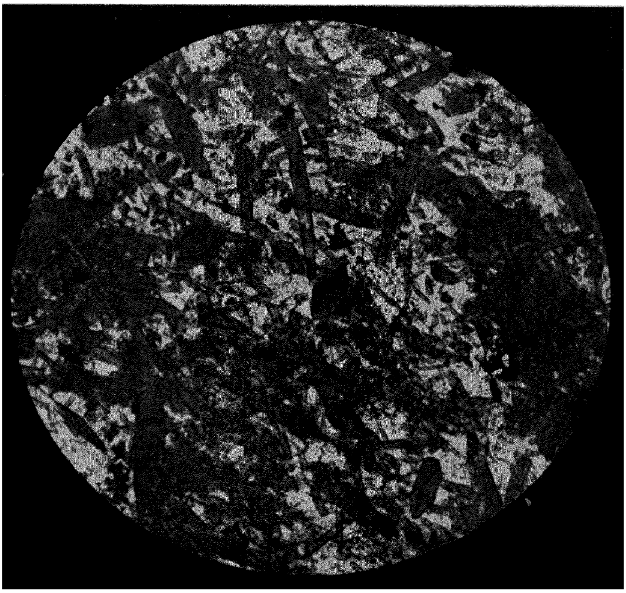

PHOTO-MICROGRAPH 8.

Epidiorite (hornblende needles).

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diorites make good building stone and excellent paving stone and setts. The andesites are perhaps the best types of material for road metal—particularly in the old class of macadam road.

BASIC ROCKS.—Gabbro, dolerite, basalt: this family of rocks is commonly spoken of as trap. They are dark green to purple in colour; their texture and variation of grain were well shown in the photomicrographs already discussed. Plagioclase felspar and augite are the most conspicuous minerals; magnetite is frequently present; olivine is also a common component. These rocks are, however, subject to comparatively rapid alteration; usually the felspar is decomposed and the augite undergoes a change as a result of which green hornblende is developed. In some cases a dolerite has been found to have been transformed by this paramorphism into an entirely different kind of rock—exactly the same in chemical composition, but with quite different minerals. This is well shown in the following photomicrographs.

No. 6 gives an idea of a dolerite in the process of alteration (not decomposition) by recrystallization. This phase is followed by the growth of needles of green hornblende on the margins of the augite and the development of the mineral apatite.

No. 7 shows a complete transformation of the augite into green hornblende. The felspar has also recrystallised into a more stable variety. The rock is a true epidorite, because there is enough evidence to indicate its origin; it is uncommonly tough and strong.

No. 8 shows very clearly the growth of the green hornblende in accicular crystals. The augite has been entirely converted, and fresh felspar has also developed at the expense of the original felspar. The rock is exceedingly tough and durable, and is known as an epidiorite; it is, however, not always possible to say if this rock is of secondary origin or an original diorite. The basalts make excellent road metal because, by their alteration, secondary minerals develop which make the whole metalling more compact. Blocks of doleritic basalt, such as the Rowley Rag, have long been utilised as paving setts because of their toughness and resistance to abrasion. Dolerite also makes good paving stone, and is always a strong building stone. Unlike the granitic rocks, which can be obtained in monoliths of great size, it is usually difficult to quarry blocks of anything like the same proportions. The basic rocks are more heavily jointed by closer-spaced joints, possibly because of the greater contraction which takes place when the molten material solidifies. The average crushing stɹength of doleritic basalt is, roughly, 1,000 tons per square foot, some epidiorites being stronger. The specific gravity of these rocks varies from 2.90 to 3.10, or a little more. A block of a cubic foot weighs, approxi-

mately, from 175 to 185 lbs. One word of warning is, however, necessary with regard to the use of basalt for road metal: basaltic trap, when badly decomposed, becomes earthy, but it is not the strong material which has been discussed, consequently the same results cannot be obtained by using the soft-weathered material.

ULTRA-BASIC ROCKS.—Dunite, peridotite, limburgite: there is a dispute as to whether these three names refer to the rocks of plutonic, hypabysal, and volcanic origin. The whole family is peculiar; some types consist almost entirely of augite or other pyroxene mineral, others are practically pure aggregations of olivine, while combinations of these are common—in some cases including plagioclase felspar. The texture is generally coarsely ophitic. The rocks are liable to comparatively rapid decomposition when subject to prolonged weathering. They pass by paramorphism into serpentine, talcose, and similar rocks of secondary origin. When fresh, some varieties are tough, but as they are not extensively used—except as ornamental stone because of the beautiful play of colour which some polished specimens show—there is little reliable information regarding their crushing strength. The specific gravity varies from 3.00 to 3.30, and a cubic foot weighs on an average 180 to 190 lbs.

SEDIMENTARY ROCKS.—The materials which compose sedimentary rocks have in most cases been deposited in a more or less horizontal position under water. The subsequent consolidation of the detrital material into beds of rock is generally effected by the weight of later deposits. The characteristic feature of the sedimentary rocks is their stratification; the several layers may be thin or thick, the resultant rock being laminated or bedded. A number of such beds may be conformably superposed, and thus constitute a series. In some cases one such series may be found to overlie another series of rocks in an uncomformable manner. There is often, owing to conditions of deposition being different, a change in the composition of the beds when traced laterally; this difference of composition is more evident in the upward or downward section of a series of beds. Photograph 3 shows false-bedded sandstones which are a conformable part of the strata seen in the view. Beds of coarse gravel may be overlaid by sandy layers, and these in turn may be covered by laminated clays which pass upward into beds of limestone. Such a section would clearly indicate great geographical changes. The coarse gravels having been deposited by swift-flowing rivers, the clays probably settled in the quiet waters of a lake or sluggish river; while the limestone would suggest that the area finally sank beneath the sea. The individual grains which compose the materials of most sedimentary rocks, conglomerates, sandstones, etc., are nearly always rounded:

their shape may often be a guide to the mode of formation of particular beds. For example, river pebbles, because they are steadily rolled in one direction (down-stream), tend to assume the shape of prolate spheroids, the axis of the spheroid being horizontal and longer than the diameter of the circular section; seashore pebbles, on the other hand, because they are pushed and pulled up and down the beach by the rising and receding tides, are flat; they assume the shape of oblate spheroids, the axis of the spheroid being vertical and shorter than the diameter of the circular section. River sand is, as a rule, sharper than sea sand, owing to its being nearer its source of origin, and consequently less worn and rounded.

TEXTURES AFFECTING POROSITY.—The rounded grains of sedimentary rocks touch each other without interlocking when the material becomes consolidated; a considerable portion of the rock is therefore empty unless filled later with a cementing matrix (see Photomicrographs Nos. 9 and 10). The volume of this interstitial space, as compared with the total volume of the rock, varies greatly; in clays and soft chalk the pore-space volume may be as much as 50 per cent. of the whole volume of the material; in soft sandstones it may vary from 20 to 30 per cent.; in hard sandstones the porosity may be only 15 per cent.; slates and shales have a porosity less than 6 per cent.; hard, massive limestones have a smaller amount of pore-space, sometimes less than 3 per cent.; fine-grained quartzites and most igneous rocks are practically impervious, their porosity not exceeding 1 per cent. The porous or impervious nature of a rock is dependent on the size of the pore-spaces; clays—although with a large interstitial volume—are practically impervious, because the pore-spaces are exceedingly small; the dry material is, however, capable of absorbing appreciable quantities of water; chalk is porous because the pore-spaces are relatively large; sandstones are porous for the same reason; quartzites, on the other hand, are not only impervious, but they do not absorb water; the same is true for the massive limestones (see Photomicrograph No. 11). In these rocks it is the fissures and joints which hold large volumes of readily given-up water.

CLASSIFICATION.—The commonest types of the sedimentary rocks are varieties of sandstones (arenaceous type), clays and shales (argillaceous type), and limestones (calcareous types). The relative abundance of these rocks in the crust of the earth has already been discussed. The chemical composition has also been indicated on a previous page.

SANDSTONES.—Several varieties of sandstones occur; some with a porous texture and others with an interstitial matrix of material such as carbonate of lime, ferric oxide, silica, etc. The aggregate

usually consists of grains of quartz; the rock may be coarse or fine grained, friable (soft) or compact (hard). Their specific gravity varies from 2.65 to 3.00, and the weight per cubic foot of blocks may be 160 lbs. for the porous types and 175 lbs. for varieties with a ferruginous matrix. Porous sandstones are generally not as strong or as durable as the cemented types; much, however, depends on the degree of consolidation of the porous varieties. The average crushing strength of hard, coarse-grained sandstones is about 600 tons per square foot, as against 400 tons per square foot for fine-grained types. They may occur in massive beds with few joints, and may at times allow of the quarrying of enormous blocks. Large slabs are often obtainable from thinner beds; such slabs can be cut up into stone pillars or into paving flags. Laminated sandstones are not rare, and frequently produce excellent flagstones, particularly those varieties with appreciable quantities of felspar. Westminster Abbey, begun in the reign of Henry III, 1272–1307, is largely built of calcareous sandstone (Reigate stone) from the Upper Green-sand (Cretaceous) of the Weald. It has not stood the test of time very well, and repairs have usually been carried out with oolitic limestone (Portland stone, etc.).

SHALES AND CLAYS.—These argillaceous rocks are nearly always fine-textured and often laminated. They, however, vary in composition: some types merge into the sandstones, while others are intimately related to the limestones. The soft clays differ greatly in composition—from ferruginous brick-clays to cream-coloured fire-clays. The more compact shales are the least useful, as they are generally too hard to pug for brick-making and too soft to use for building purposes. The hard slates, on the other hand, are most valuable, as they have one well-developed, closely-spaced cleavage. Some good roofing slates have a crushing strength equal to that of granite, *i.e.* 800 tons per square foot, and they stand a transverse load better than any other kind of rock. Softer clay slates have a crushing strength of about 400 tons per square foot. The normal shales are much weaker. The specific gravity of shale is about 2.60, and a cubic foot weighs, roughly, 155 lbs.; slate, on the other hand, has a specific gravity of 2.72, and a cubic foot weighs, approximately, 170 lbs.

LIMESTONES.—These rocks vary considerably in colour, structure, and texture. They may be white, grey, pink, brown, or black, and occur in great massive beds or in thinly laminated strata or in soft deposits of chalk. In many instances they consist largely of coral or other calcareous fossil matter such as shells, crinoids, etc.; in other cases they are unfossiliferous. The texture may be amorphous, oolitic, granular, or compact and crystalline. All limestones are

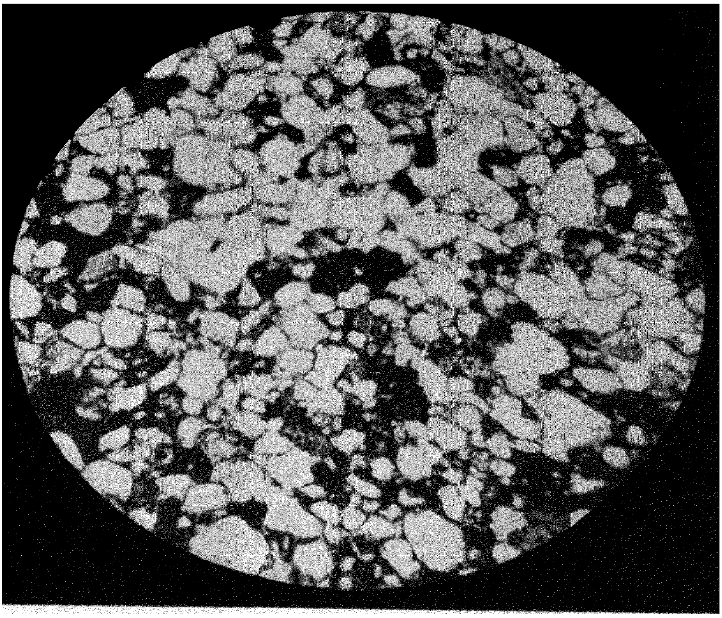

PHOTO-MICROGRAPH 9.
Ferruginous Sandstone.

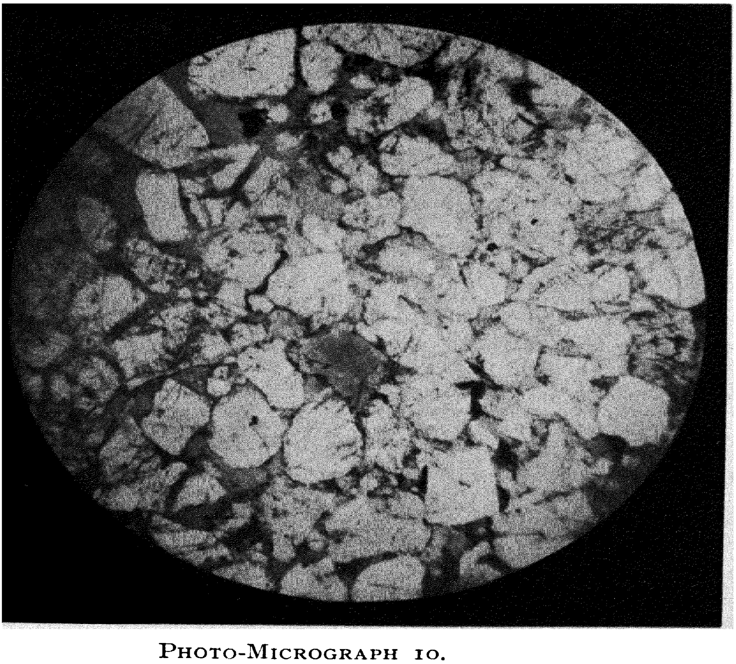

PHOTO-MICROGRAPH 10.
Sandstone (secondary silica).

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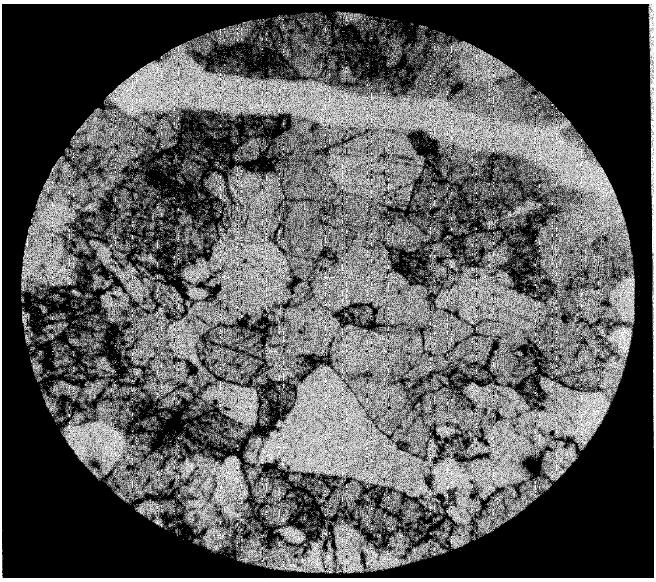

PHOTO-MICROGRAPH 11.
Marble (crystalline limestone).

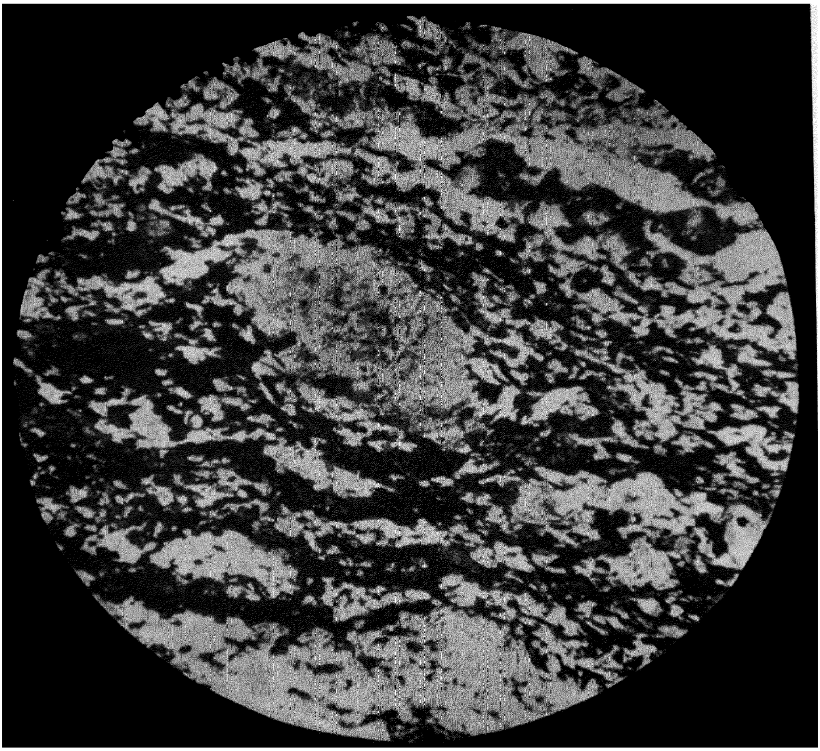

PHOTO-MICROGRAPH 12.
Augen gneiss.

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soluble in water, particularly water charged with acids. Calcium carbonate is the predominant constituent of limestones, although certain dolomitic varieties containing magnesium carbonate are common. These types are usually more insoluble than the pure true limestones.

Limestones are of great importance to an industrial country; they are useful for building stone, in making lime, cement, and as flux for ironworks, etc. Much depends on the physical strength and chemical purity of the stone in deciding its most advantageous disposal. The specific gravity of hard massive limestone is about 2.70. A cubic foot of this type of rock weighs as much as 170 lbs., whereas an equal volume of chalk weighs, roughly, 120 lbs. The crushing strength of a good hard limestone is roughly 400 tons per square foot. The hardest normal limestone can be easily scratched with a steel knife, and all limestones effervesce when treated with an acid; hard limestones are consequently very much softer than compact massive sandstones. During recent years certain peculiarities have been noticed in connection with the adhesiveness of various minerals and rocks to grease and tar. The modern practice of protecting the surface of roads with an asphaltic carpet has resulted in the use of greater and greater quantities of hard massive limestones as road metal; the tar is drawn down into the crevices between the fragments, and effectively reduces the grinding action which takes place between these fragments in the bed of the road when the road is subjected to heavy traffic. In such cases the "metalling" should be laid dry, tarred, rolled, and surfaced, without the application of water.

TRAVERTINE.—It is well known that the formation of stalactites and stalagmites in caves and overhanging masses of calcareous tufa in waterfalls are due to the evaporation of dripping water containing calcium carbonate in solution. These phenomena are common enough in limestone areas, so that the engineer is not worried about lime for building purposes; quite large deposits of calcareous material, of sufficient purity to provide lime for building purposes, are occasionally found below springs and in streams which drain other rocks. Thus the basic rocks, basalt, dolerite, etc., contain on an average 12 per cent. of lime; this is leached out by meteoric waters containing carbonic acid, and carried into the spring and stream water. During dry periods, when the stream flow is weak and evaporation great, appreciable quantities of tufa are deposited year by year until a large deposit accumulates. There are numerous places in the basaltic areas of the Deccan and the Central Indian Highlands where such deposits of travertine are found and the trap soil is generally full of "kunkur," which has a similar origin.

A calcareous sandstone, *i.e.* where the grains of sand of a porous sandstone are cemented with calcium carbonate, is also formed in the same way. The use of "kunkar" lime—the "kunkar" nodules being collected by hand from the surface of the soil—probably saves engineers in India many hundreds of pounds in railway freight as, in the absence of this tufa limestone, lime would have to be obtained from limestone areas.

From an engineering point of view, perhaps, the following extracts with regard to the natural bridge of travertine in the Gokteik gorge in Upper Burma will be of interest. It is not possible to do better than use Mr. T. D. La Touche's own words (see *Rec. Geol. Surv. India*, Vol. XXXIII, Part I, 1906, pp. 49–50).

One of the principal obstacles to the construction of the Mandalay-Lashio Railway, originally intended to connect Burma with S.W. Yunnan across the Northern Shan States, was the existence of a deep gorge, with almost perpendicular sides, about midway between Maymyo and Lashio . . . there was no possibility of avoiding" the Gokteik gorge. "At Chaungzon the depth, measured from the surface of the plateau at Nawnghlio, is about 1,500 feet, which gradually increases to about 2,000 feet" lower down.

"In selecting a site for the railway viaduct, advantage was taken of the fact that at about 2 miles below Chaungzon the river is spanned by a 'natural bridge,' the upper surface of which is 550 feet above the river, and upon this the principal pier of the viaduct, a fine structure of steel, has been founded. The greatest height of the viaduct, at the point where it rests upon the natural bridge, is 320 feet, and the total height from the bed of the stream to rail-level is somewhat under 900 feet. Thus the descent from the plateau, and the ascent to it on the opposite side of the gorge, has been reduced to about 600 feet, and though the gradients are very heavy, generally speaking about 1 in 40, they are not excessive.

"The section of the gorge at the place where the railway crosses it is peculiar. The upper portion, down to the level of the natural bridge, has gently sloping sides on the southern bank, while the north bank is quite precipitous. This feature is due to the fact that the limestone rocks, out of which the gorge is excavated, dip towards it on the southern side, so that the tendency of the river has been to cut back the northern bank into a series of perpendicular cliffs. But from the top of the natural bridge to the river the sides are more or less perpendicular on both sides, and very close together, so that the river runs in a deep narrow trench invisible from above, until one is crossing the viaduct immediately above it. The effect of this sudden glimpse into the profound depths of the gorge, as the train slowly rolls across the bridge, is curious, and one not likely to be forgotten by anyone who has ever experienced it.

"The excavations made for the foundations of the railway viaduct in the top of the natural bridge, and in the sides of the gorge immediately above it, show that the natural bridge itself is composed to a

great extent of travertine or calcareous tufa, deposited from water saturated with carbonate of lime, on the evaporation of the water. The cuttings of the railway as it descends both sides of the gorge also show that the ground is covered, often to a considerable depth, with deposits of the same travertine. This, there is no doubt, has been deposited by the streams which flow into the gorge from either side. Great curtains of it may be seen hanging from the cliffs on either bank . . . the precipitous sides of the gorge being very close together, the travertine has gradually grown out from the sides, from the southern side especially, forming a kind of bracket or shelf, overhanging the river, until it has met and coalesced, forming a true ' bridge.' "

METAMORPHIC ROCKS.—Literally, any altered rock is a metamorphic rock, and, strictly speaking, the sedimentary types previously described are of this class. However, for purposes of utility, the term metamorphic is used only for those representatives of the igneous and sedimentary rocks which have been subjected to great static pressure or exposed to intense dynamic force, or influenced by both, deep within the earth's crust, and have, as a result, undergone a noticeable change in structure, texture, or mineral composition.

An approximate estimate of the increase of pressure with increased depth, in the case of a rock with a specific gravity of 2.6, is shown below:

Depth in metres	Pressure in kilograms per sq. cm
10	2.6
100	26.0
1,000	260.0
10,000	2,600.0
20,000	5,200.0
40,000	10,400.0

The temperature gradient is roughly 1° C. per 30 metres.

Various writers have followed Van Hise (see " Treatise on Metamorphism ") and have considered the rocks of the earth's crust as being in one or other of the following depth zones:

Katamorphism, the " Vadose " region or belt of weathering which lies above the level of the stationary ground water and in which the rocks are subjected to the leaching action of percolating waters.

Metasomatism or belt of cementation which lies below the level of the stationary ground water. In it the rocks are cemented with silica, lime, iron oxide, etc., or undergo chemical replacement, *e.g.* limestone by dolomite, limestone by ferric oxide, etc.

Anamorphism, in which high temperatures and pressures prevail and static pressures and dynamic forces are active. It is generally in this zone that foliation is developed and recrystallization takes place.

Grubenmann, in "Die Kristallinen Schiefer," zweite Auflage, p. 80, gives the following table for the zones and stresses in the earth's crust:

Earth crust	Temperature Reaction		Hydrostatic pressure	Stress	Metamorphic action
I. Upper zone ...	Moderate	Exothermic	Small	Strong	Mechanical
II. Middle zone ...	Higher	Exothermic (also endothermic)	Stronger	Very strong	Chemical (volume changes)
III Deep zone ...	Very high	Endothermic	Very strong	Weak	Chemical (Re-crystallization unaffected by volume changes

In Zone II the volume is affected by the pressure, owing to the temperature not being high enough to counteract the effect.

In Zone III the temperature is so high that the pressure effecting the formation of minerals of maximum specific gravity does not apply.

ORTHO-GNEISSES AND SCHISTS.—Great static pressures seldom produce any change in the texture of igneous rocks, although in some cases new minerals may result by the paramorphic or metathetical redistribution of the components of the rock. Dynamic forces, on the other hand, induce a structural foliation and result in the formation of the so-called ortho-gneisses and ortho-schists, *i.e.* gneisses and schists which have been produced by the dynamic metamorphism of igneous rocks. This foliation or schistosity produces a banded or bedded type of rock which is often far superior to the normal igneous rock in resisting transverse strain. Occasionally an extreme phase of metamorphism, known as "mylonitisation," develops. This results when the pressure is so intense and shearing strains so pronounced that all the original structure of the rock is destroyed. It is particularly well developed along the zone of intense shear fracture. The term granulitisation is applied to a similar effect: this name is restricted to those cases where the rock has been caused to "flow" but where no fracture has resulted.

The foliation planes of weathered gneisses and schists constitute channels for the percolation of water, so that it is advisable, when

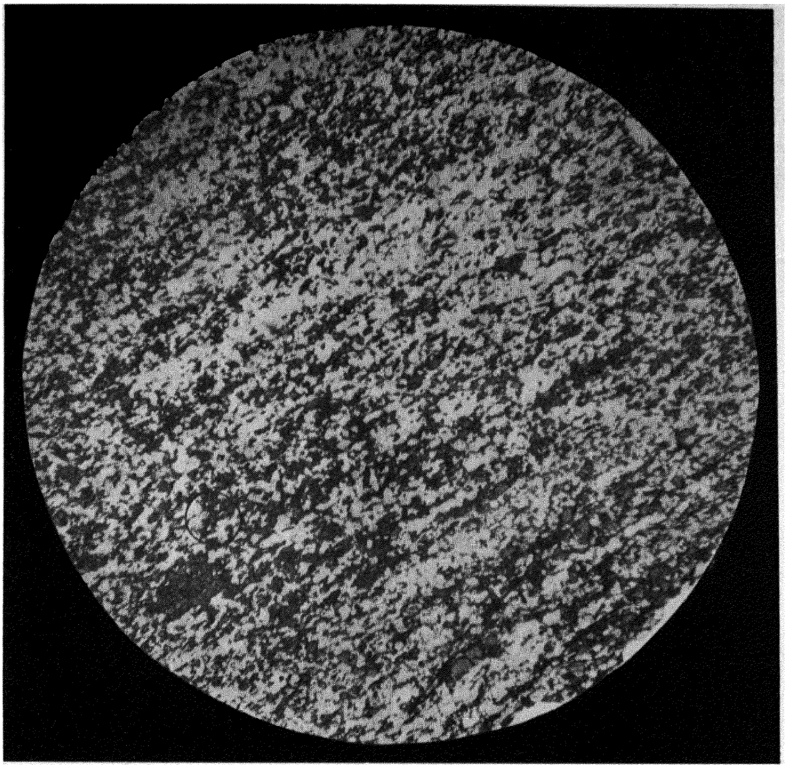

PHOTO-MICROGRAPH 13.
Schistose gneiss.

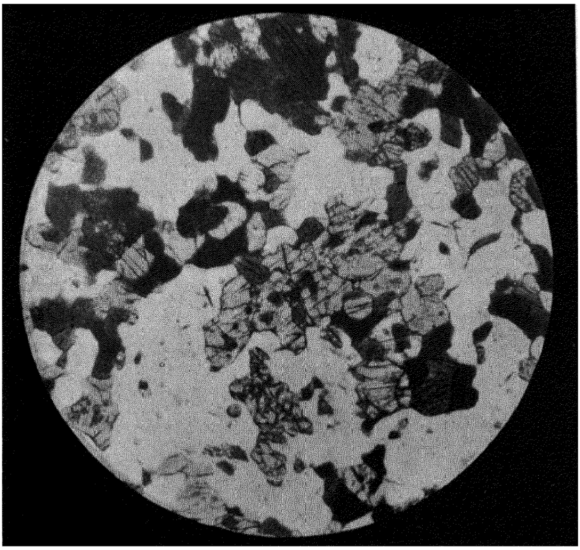

PHOTO-MICROGRAPH 14.
Granulite (diopside and calcite).

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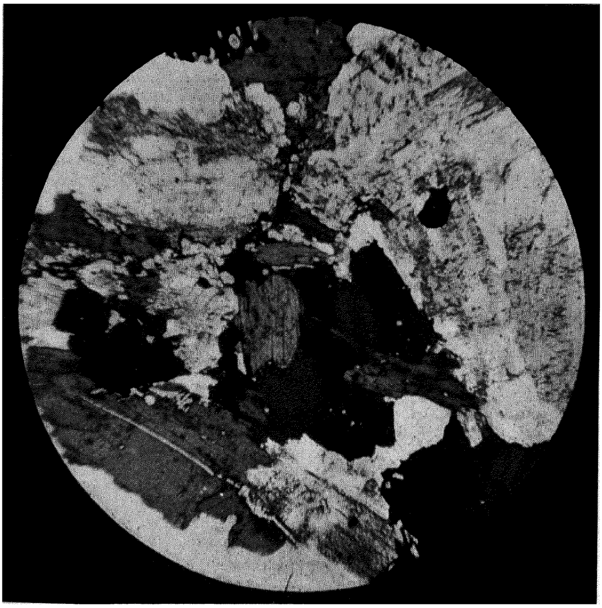


PHOTO-MICROGRAPH 15.
Typical granite.

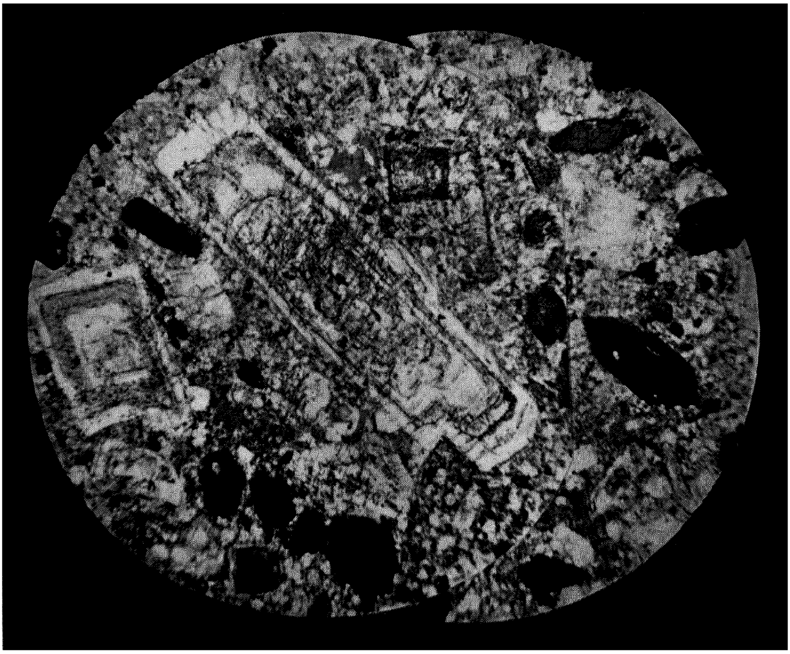


PHOTO-MICROGRAPH 16.
Hornblende syenite. Shows a true syenite, with zoned crystals of felspar and dark idomorphic crystals of green hornblende. Specimen obtained from a block of paving-sett in Marseilles.

[*To face page* 53.

locating dam sites on such rocks, to have the length of the dam parallel to the direction of foliation. The gneisses and schists can generally be readily quarried and dressed for building purposes. Their crushing strength (on bed) is similar to the igneous rocks to which they are related. Some varieties have great resistance to transverse strain and can be used as stone beams. The specific gravity and weight per cubic foot are also similar to the igneous rock groups. Some granitoid types are coarse-textured, but the more severely sheared schistose types have a fine-grained texture.

Photomicrograph No. 12 shows a thin section of a coarse "augen" gneiss, as seen under the microscope. In many cases the same appearance, on an even larger scale than is shown in the photograph, is visible in hard specimens. Photomicrograph No. 13 represents the section of a schist with granular texture. Photomicrograph No. 14 gives an excellent idea of the granular texture of certain types of metamorphic rocks which have undergone re-crystallization. It may here be mentioned that re-crystallization usually takes place when the dynamic forces of metamorphism are replaced by static pressures at, so to speak, annealing temperatures. Photomicrograph No. 15 is a section of a biotite granite.

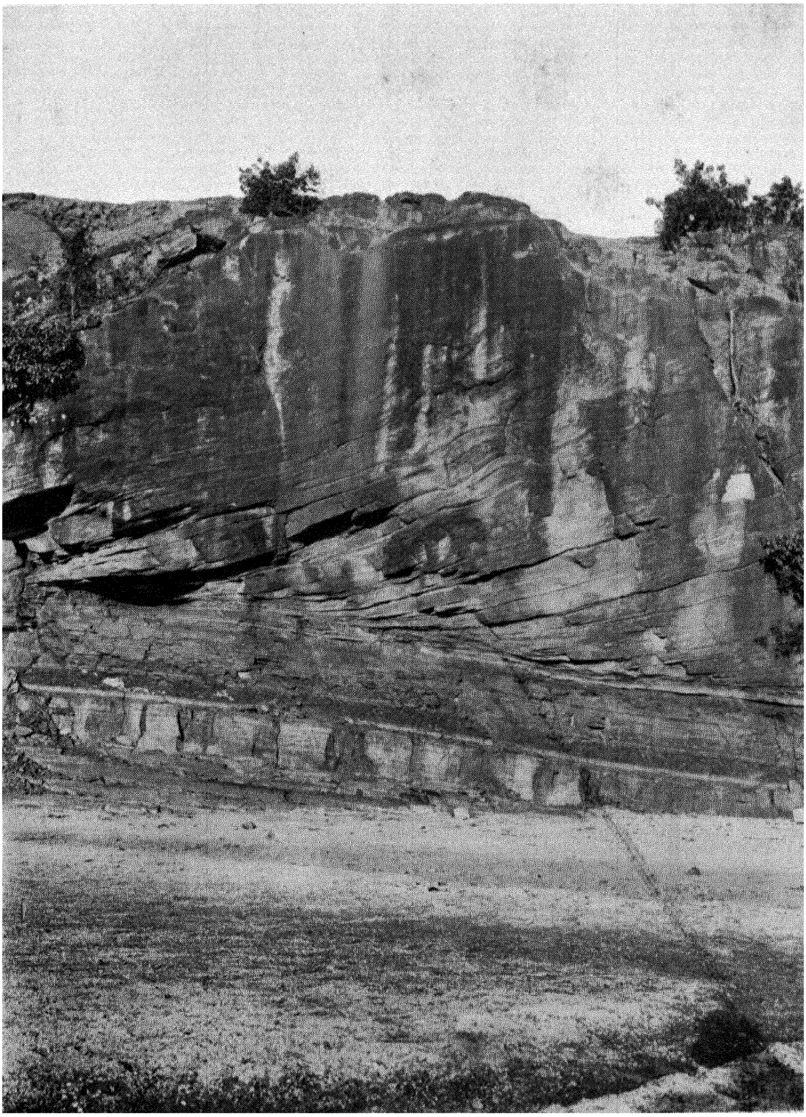
PARAMORPHIC TYPES.—The sedimentary rocks—the sandstones, clays and shales, and the limestones when subjected to enormous static pressure or severe dynamic strain, or combinations of these forces—undergo very important changes. Under great pressure the sandstones are converted into quartzites, the shales become clay-slates and slates, the limestones become crystalline (marble). In each of these cases, the metamorphic representative is generally more dense in texture, superior in strength, and far more durable than the original rock. When subjected to dynamo-metamorphism, foliation or banded structures are induced, and certain characteristic minerals develop. The shales or slates are converted into phylites, mica-schists, staurolite-schists, and sometimes into gneisses (the coarser texture being due to induced crystallization). The limestones are transformed into calcareous (calc-) gneisses, pyroxene-gneisses, crystalline limestones, marbles, etc. Photomicrograph No. 14 shows the texture of a pyroxene granulite, while Photomicrograph No. 11 is a section of a crystalline limestone. In this connection certain facts have been determined by Riecke, who has shown that

"since the solubility of a mineral is increased by pressure, solution will take place at the points of greatest pressure and crystallisation at the points of greatest relief." ("Text Book of Petrology," Vol. II, 1923: F. H. Hatch and R. H. Rastall.)

These gneisses and schists of sedimentary origin are frequently

referred to as para-gneisses and para-schists, to distinguish them from the type related to the igneous rocks. There are endless varieties of such rocks. It is almost futile to endeavour even to summarise their characteristics in this book. Their strength and durability depend largely on their component minerals and the mode of aggregation, size, and shape of the individual mineral grains. In general, the types with a granular texture are strong; those with an interlaced fibrous texture are tough; while those with insoluble component minerals have good weathering properties. Occasionally some beautiful (ornamental) varieties occur, but as a rule they are local, and possibly restricted to a single band.

Most gneisses and schists resist abrasion better when the foliation planes are perpendicular to the wearing surface. In building, it is best to have the foliation planes horizontal, so that the weight falls transverse to the foliation.



Per favour D.G.S.I.] TYPICAL FALSE BEDDING. [*Photo by Dr. C. S. Fox.*

The true bedding is seen at the base of the bank inclined gently to the right. The strata above are current bedded sandstones which suggest dips to the left, but this is false.

COAL MEASURE (BARAKAR) SANDSTONES, RANIGANY COALFIELD.

[*To face page* 54.

CHAPTER IV

MODE OF OCCURRENCE OF ROCKS

GENERAL REMARKS.—In Chapter I, under Theoretical Considerations, the Cosmical Aspects of Geology were touched upon. In Chapters II and III, the subjects of Mineralogy and Petrology have been discussed. In this chapter an endeavour is made to elucidate questions of Structural Geology.

From our observations of the accumulation of silt and the sorting influence of the currents of rivers, we know that there is a great group of rocks which must have been deposited as sediments, and subsequently buried and consolidated, and then finally upheaved to such an extent as to be now subject to denudation. These are the Sedimentary Rocks. Their chief characteristic is a stratified or bedded structure originally laid down in sheets in a more or less horizontal position, but now often found in a tilted and twisted condition. The planes separating successive sheets or beds are commonly spoken of as bedding planes. Sometimes these beds are easily separable along these planes ; often they adhere strongly. Details of these sedimentary rocks are given in a later chapter.

IGNEOUS ROCKS.—Visits, perhaps to Vesuvius or Hawaii, have brought us into direct touch with rock in a molten condition—the Volcanic, or more comprehensively, the Igneous Rocks.

ASH BEDS AND LAVA FLOWS.—True igneous rocks have several modes of occurrence. If they are extruded from deep within the earth's crust to the surface, they may quietly overflow the country as lava, or they may be ejected with explosive violence and be blown to pumice and dust (ashes). In the former case they may flow far from their point of emission and resemble, when solidified, horizontal-lying, massive, sedimentary beds. In the latter case, they are thickest near the vent of the volcano from which they were ejected. The beds of volcanic ash which have been water-sorted and consolidated into firm rock are known as volcanic tuff, or simply as tuff.

DIKES, SILLS AND BOSSES.—Igneous rocks are pushed upwards through the overlying beds in variously shaped channels. In some cases the molten matter is forced upwards across the super-

incumbent strata in sheet-like channels. When the molten matter becomes solid in these channels, the resulting rocks are called dikes. If, however, the molten rock forces its way between two gently inclined sedimentary beds, the solidified igneous rock in this channel is called a sill. If a sill is lens-shaped, it is called a lacolite. Should the molten mass force its way upward in a comparatively small circular-sectioned pipe, then the igneous rock which remains in the duct is spoken of as a plug or neck. If the plug is blunt towards the top and is of large dimensions, it may be called a boss or batholith. In most mountain ranges it is usual to find a granitic core parallel to the orographic axis of the range. It is thought by some geologists that an enormous dike-like boss has pushed up into the range. This view is questioned by other observers, who think that the granite core may not have any deep-seated connection. It may be underlaid by sedimentary or metamorphic rocks of sedimentary origin as depicted in the section shown in Fig. 56. Several exposures are known, *e.g.* all along the foothills of the Himalaya, especially well seen on the line up to Darjeeling from the plains of Bengal; also a more complex structure is found about Chor Mountain near Simla, where granitic rocks appear to be underlaid by paragneisses and unaltered sedimentary strata.* The structure is said to be due to overfolding, but this explanation is not now accepted by all geologists. These observers are inclined to believe that this apparent inversion is not due to an igneous intrusive granite which has been involved in the tectonic folding. They have reasons for thinking that the granite represents an original argillaceous sedimentary rock which has been subject to enormous static pressure without a considerable rise in temperature. The result has been that re-crystallization occurs by which new minerals occupy a minimum volume. This argument is supported by a study of granitic pegmatites in folded schistose rocks. In these folds it is not uncommon to find that irregular bodies of pegmatite occur in the bend of the folds, whereas

* This covering of younger strata by overfolded or recumbent folds of older rocks is fully recognised in the *Decken* theory of Swiss geologists in the study of Alpine structure. None of the gneisses in the Simplon tunnel area are intrusive—judging by the evidence of the unravelled structure (W. H. Bucher: "The Deformation of the Earth's Crust," 1933, pp. 195-6). "They are all lobes of the pre-Parmian crystalline basement Six such gneiss *decken* lie one on top of the other in the region south of the Rhine. The highest of these culminates in the magnificent peaks of the Dent Blanche and the Matterhorn. Pre-Triassic schists, gneisses, and granites make up the bulk of this highest *decke* in the Pennine Alps. On its underside, in inverted order, can be seen the normal sequence of Triassic and Jurassic rocks reduced from a thickness of several thousand meters to one of twenty or thirty meters, a reduction to one-hundredth of the original thickness on the average. Within the *decke*, the pre-Triassic planes of stratification and schistosity are still visible, superseded but not destroyed by the structural effects of the last deformation. It all looks as if the *decke* had flowed into its present form 'like viscous dough.' In the illustration given by Bucher the Dent-Blanche *decke* has the character of a plastically folded recumbent anticline. It consists of gneiss and other crystalline rocks. Between it and the gneisses of the underlying *decken* lies the squeezed-in recumbent syncline of Mesozoic rocks."

schistose material occupies the limbs of the folds. The forces which develop in a fold are simple; there is a strong shear effect produced in the limbs of the fold, whereas great static pressures develop in the arches. In consequence, we find the limbs of a fold are drawn out, while there is a thickening in the bends.

METAMORPHIC ROCKS.—This brings us to the subject of the intensely contorted and foliated or tightly-banded rocks. Some of these frequently appear to have a sedimentary facies, while other types have a distinct granitic aspect. Both these types constitute the so-called Crystalline Gneisses and Schists, *i.e.* the Metamorphic Rocks—metamorphic because they are the dynamically altered representatives of Sedimentary Rocks or of Igneous Rocks. The former are called Para-Gneisses and Schists, while the latter are designated Ortho-Gneisses and Schists. The planes between the laminæ or foliæ of the banded or laminated varieties are termed foliation planes. In most cases the laminæ are not easily separable along these foliation planes, but often an easy parting is possible.

The term foliation is applied to those banded metamorphic rocks which have a laminated arrangement of minerals. The word schistose is applied when the rock is finely laminated; in both cases the structure is evidently due to shearing. Schistose rocks usually have the mica sericite prevalent, and the laminæ are usually bent, crumpled and contorted. Rock cleavage, on the other hand, is due to pressure, and is the term most frequently applied to those rocks which can be split into slabs of considerable size.

FOLIATION PLANES.—The foliation planes of banded metamorphic rocks can be treated for purposes of measuring their strikes and dips in the same way as the bedding planes of the sedimentary rocks. If traced for some distance along their strike, these banded rocks either show lenticular structures or the banding appears to continue although the composition of the band alters. The gneisses and schists sometimes contain small or large inclusions (intrusions ?) of lens-shaped, lenticular-sectioned, very coarse-grained, granitic rocks. These intrusive lenses are known as pegmatites. In some places these pegmatites are found in particular zones of the banding, and in other places they are seen to cross the lines of banding in an irregular manner. It is for this reason that they are thought to be intrusive into the banded rocks, and are commonly classed as igneous rocks of a particular type.

STRIKE AND DIP.—In recording the tilt or slope of bedded or foliated rocks, it is usual to make all measurements with reference to a horizontal plane. The same is true with regard to fault planes and cleavage joints. The direction or strike of a bed, fault, or joint is

the bearing of the line which a horizontal plane makes with the plane of the bed, fault, or joint. The slope or dip of a bed or fault plane is the maximum angle, at a given locality, which the bedding plane makes with a horizontal plane. The direction of dip is always at right angles to the strike at the same place, but, as the dip may be in one or other of two opposite directions, particular care should be taken in stating the actual direction.

It is usual to measure and to state the dip of strata in degrees. The declivity of a surface, whether bank, road, or steam bed, is usually

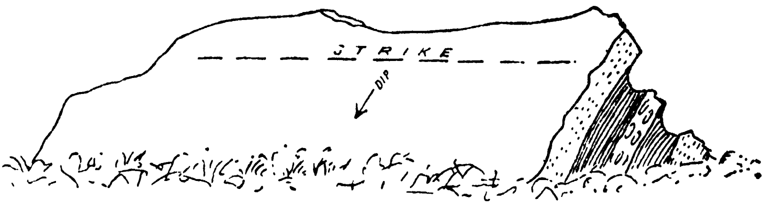


FIG. 1.
Dip and strike.

stated as 1 in x measured horizontally. This fraction $1/x = \tan \lambda$ where λ is the angle of slope. Very occasionally the gradient is stated as 1 in y where y is measured along the surface of the slope. In this case $1/y = \sin \lambda$. These gradients are shown in the table below.

Slope in degrees	Gradient	
	Horizontal tan of ∠	Along the slope sin of ∠
1	1 in 57	1 in 57
2	1 in 28.6	1 in 28.6
3	1 in 19.1	1 in 19.1
4	1 in 14.2	1 in 14.3
5	1 in 11.4	1 in 11.5
6	1 in 9.5	1 in 9.6
7	1 in 8.1	1 in 8.2
8	1 in 7.1	1 in 7.2
9	1 in 6.3	1 in 6.4
10	1 in 5.7	1 in 5.8
15	1 in 3.73	1 in 3.86
20	1 in 2.75	1 in 2.83
25	1 in 2.15	1 in 2.35
30	1 in 1.74	1 in 2
35	1 in 1.43	1 in 1.74
40	1 in 1.19	1 in 1.56
45	1 in 1	1 in 1.42

Depth to stratum for various dips from an out-crop (at same level) at different distances D (depth $= D \tan \theta$).

Angle of dip	100	200	300	400	500	600	700	800	900
			Distance from out-crop						
1	1.75	3.50	5.25	7.00	8.75	10.50	12.25	14.0	15.75
2	3.49	6.98	10.47	13.96	17.45	20.94	24.43	27.92	31 41
3	5.24	10.48	15.72	20.96	26.20	31.44	36.58	41.92	47.16
4	6.99								
5	8.75								
6	10.51								
7	12.28								
8	14.05								
9	15.84								
10	17.63	35.26	52.89	70.42	88.15	105.78	123.41	141.04	158.67
11	19.44								
12	21.26								
13	23.09								
14	24.93								
15	26.80								
16	28.68								
17	30.57								
18	32.49								
19	34.43								
20	36.40	72.80	109.20	145.60	182.00	218.40	252.80	291.20	327.60
21	38.39								
22	40.40								
23	42.45								
24	44.52								
25	46.63								
26	48.77								
27	50.95								
28	53.17								
29	55.43								
30	57.74	115.48	173.22	230.96	288.70	346.44	404.18	461.92	519.66

The width of out-crop of a given bed depends largely on the dip of the bed and the slope of the ground—thus in Fig. 2, B, C, D and E, W_2 is greater than W_4 for the same bed, because the rocks are more steeply inclined and the slope of the ground and the dip of the beds is in the same direction in the latter position. Similarly, the inclination of the ground modifies the width of an out-crop when the dip is opposed to the slope—thus W_3 is greater than W_2, although the beds are the same and have equal dips. The ground surface at W_4 is less steeply inclined than at W_2, but the out-crop is wider, because the dip is in the same direction at W_4 and opposed in W_2.

Occasions often arise when it is important to endeavour to calculate the depth at which a certain bed of rock, say a coal seam, will be encountered by a boring or a shaft. As an example, suppose a coal seam (of unknown thickness and unknown out-crop, but associated with strata which dip at 30° to E. 30° S.) out-crops at X, N. 30° W. of Y, the point where the proposed boring is to be located, and that X is 1,000 yards from Z on the map (*i.e.* horizontally). The nearest point on the surface at which the coal seam will pass Y will be at Z (the prolongation of the strike), 1,732 yards away. It is assumed that prospecting at Z the coal has not been seen because of a covering of alluvium.

If Z and Y are on a level, then the depth at which the boring at Y will reach the coal will be 1,732 tan 30° = 1,000 yards. (Fig. 2A.)

If Y is considerably above Z in height, the difference of height must be added to the depth of the boring. Should Y be at a much lower altitude than Z, then the difference of height will be substracted from the calculated depth, and the boring will not have to go so deep. This shows the advantage of placing the boring after preliminary investigation.

When the core of a coal seam or other bed of rock is measured, a little consideration will show that it must be greater than the real thickness of the coal seam. In actual practice the core of a coal seam is very fragmentary, even when obtained with the best type of core drills. The use of percussion drills for proving coal seams is quite unsatisfactory.

The true thickness (t) of the coal seam must be l (the length of the core) multiplied by the cosine of the angle of dip, θ. In this case, supposing the measured core to be 12 feet, then the real thickness of the seam is $\frac{12\sqrt{3}}{2} = 10.392$ feet, or over 10 feet 4½ inches.

This formula of $t = l \sin \theta$ will apply to all beds encountered in boring wells, if it is remembered that t = true thickness, l = measured vertical thickness, and $\theta = \angle$ of dip.

The width of an out-crop of bedded rock depends on the slope of the ground surface, the dip of the bed, and the true thickness of the bed. As it is generally possible to measure the width of the out-crop W, the angle of the slope of the ground λ, and the dip of the strata θ, the true thickness of the bed can be easily calculated.

(I) When the ground surface is horizontal, *i.e.* $\lambda = \theta$ and the dip of the strata, θ, is known, and the width of the out-crop W is measured, then $t = W \sin \theta$, and $W = \frac{t}{\sin \theta}$.

(II) When the surface is inclined at λ and these rocks dip into the hill at $\theta°$ and the outcrop width is W

$$t = W \sin (\theta + \lambda)$$

$$\text{and } W = \frac{t}{\sin (\theta + \lambda)}$$

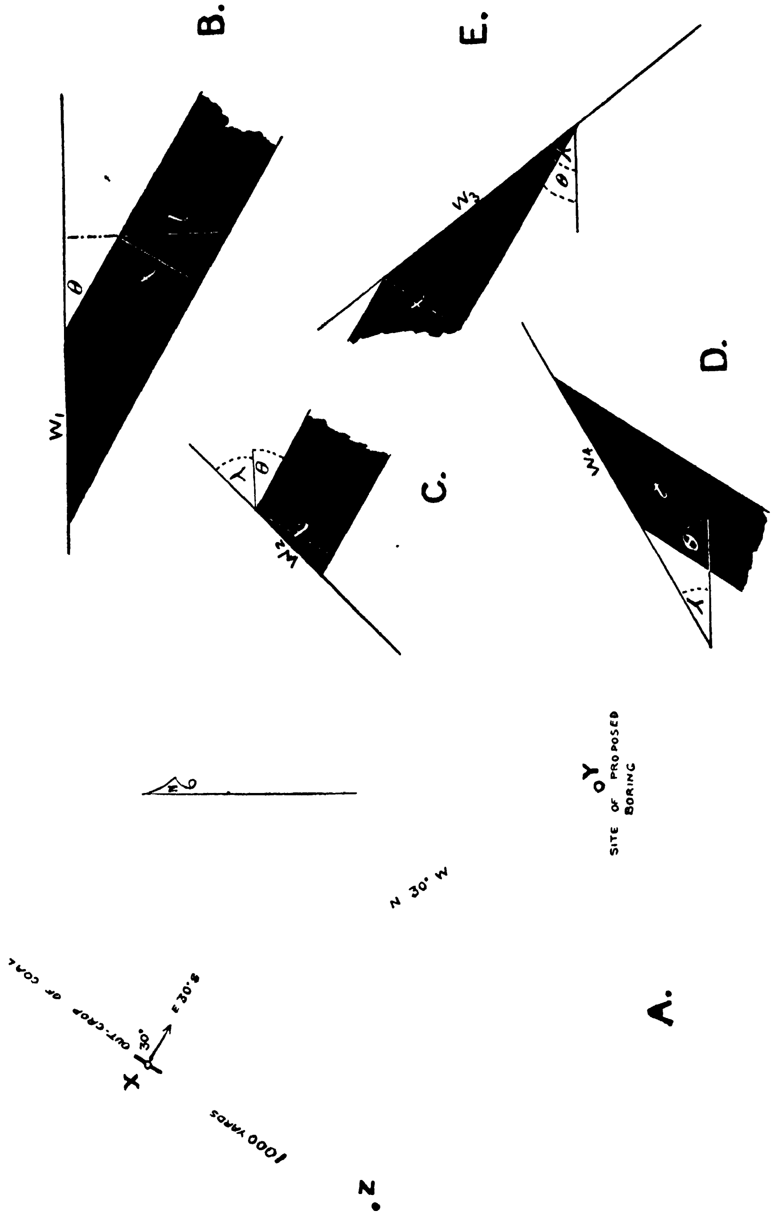
If $\theta + \lambda = 90°$, then $W = t$

(III) When the slope and dip are in the same direction but $\theta > \lambda$

$$t = W \sin (\theta - \lambda) \text{ and}$$

$$W = \frac{t}{\sin (\theta - \lambda)}$$

when $\theta = \lambda$ the strata lei along the slope.



(Plan) (Section).

FIG 2

Outcrop and thickness of beds

(IV) When the slope and dip are in the same direction, but $\lambda > \theta$ then $t = W \sin(\lambda - \theta)$ and

$$W = \frac{t}{\sin(\lambda - \theta)}$$

It is in this last case that a hill slope becomes theoretically unsafe, particularly when θ exceeds the angle of repose of the strata.

(V) Finally, when the slope is λ and the strata is horizontal

$$t = W \sin \lambda, \text{ and}$$

$$W = \frac{t}{\sin \lambda}$$

Thus it is seen there is a general formula $t = W \sin(\theta \pm \lambda)$, depending on whether the inclination of slope and dip are in the same or in opposite directions.

A certain amount of caution will obviously be necessary when dealing with faulted ground. The dip (or hade, as it is technically called) of a fault plane is measured from the vertical plane (a in Fig. 3A). Now, if a boring were to be put down on the down throw side of the fault at A, it is quite possible that neglect to place the boring tackle far enough over from the outcrop of the fault plane may result in the boring meeting the fault plane at B, and, although sunk far below the coal at C, would miss it altogether.

To obtain depth of strata (h) at a point horizontally distant (H) from the out-crop

$$h = H \tan \theta$$

To obtain thickness (t) from vertical thickness I

$$t = I \cos \theta$$

To obtain gradient ratio, find $\tan \theta$.

To find thickness t from out-crop

$$t = W (\sin \theta \pm \lambda)$$

(All the above are natural tangents, cosines and sines.)

JOINTS AND CLEAVAGE PLANES.—The divisional planes or cleavage cracks or joint fissures which are so common in all large masses of rocks are miniature faults. They are indicative of shrinkage by compression or contraction. When a molten mass, such as a basaltic lava flow, cools and solidifies, an enormous amount of contraction takes place.

In his book "The Problem of Volcanism," 1914, J. P. Iddings, speaking of the contraction of molten lavas on cooling to the solid state, says (p. 96):

"The volume of molten magmas at the time of crystallisation must be greater than that of their cold glasses. . . . In the case of diabase,

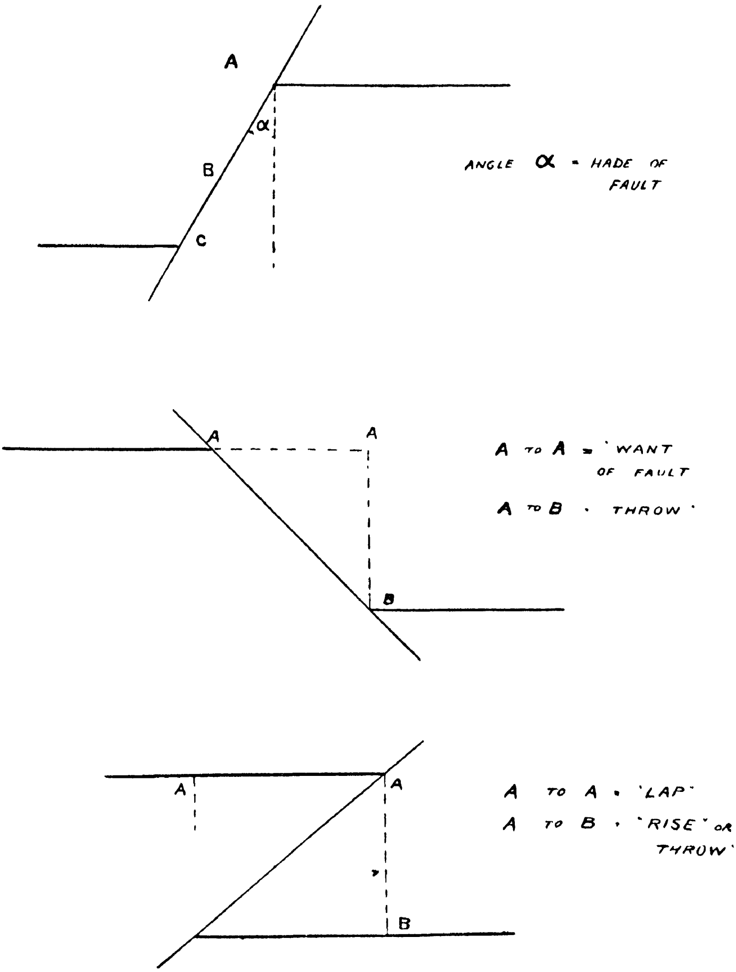


FIG. 3.
Throw and *want* of faults
(*Seen in Section*).

or basalt, from near Fairview, New Jersey, the difference between the volume of the magma at 1,250° C. and that of the cold rock has been estimated by Sosman to be 12.53 per cent. of the liquid phase."

He gives the following figures for various minerals and rocks :

	Crystal (specific	Glass gravity)	Percentage increase	
Quartz	2.650	2.213	19.74	Larsen
	2.663	2.228	19.52	Deville
Enstatite	3.175	2.743	15.74	Larsen
Diopside	3.275	2.830	15.71	Larsen
Adular St. Gothard ...	2.575	2.370	8.65	Douglas
Albite Ab_1 laboratory ...	2.605	2.382	9.36	Day and Allen
Ab_2 An_1	2.660	2.483	7.18	"
Ab_1 An_1	2.679	2.533	5.76	"
Ab_1 An_2	2.710	2.591	4.59	"
Anorthite An	2.765	2.700	2.41	"
Leucite, Vesuvius ...	2.480	2.410	2.90	Douglas
Quartz-porphyry, Montreuillon ..	2.576	2.301	11.95	Delesse
Granite, Flamanville ..	2.680	2.427	10.42	"
Fine-grained granite, St Brieuc	2.751	2.496	10.21	"
Granite, Peterhead ...	2.630	2.376	10.69	Douglas
Granite, Shap Falls ...	2.656	2.446	8.58	"
Hornblende granite, Coralvilliers	2.643	2.478	6.65	Delesse
Syenite, Plauen	2.724	2.560	6.40	Douglas
Diabase, near Fairview, N.J.	2.985	2.778	7.48	Sosman
Diorite, Guernsey ...	2.833	2.680	5.70	Douglas
Gabbro, Carrock Fell ...	2.940	2.791	5.41	"
Anorthite-basalt, Mt Hecla...	2.844	2.718	4.63	Delesse
Dolerite, Whin Sill ...	2.925	2.800	4.46	Douglas
Olivine dolerite, Clee Hills	2.889	2.775	4.14	"

On page 100 Iddings gives the melting points of various minerals, and shows that most minerals melt between the temperatures of 900° to 1,500° C., while a few melt below 1,900° C.

The stress which accompanies this contraction develops a strain beyond the elastic limits of the rock, and produces a series of more or less regularly-spaced joints. The almost perfect columnar structure seen at the Giant's Causeway in County Antrim, Ireland, and at several other places in various parts of the world, are examples of contraction joints of this type (see Fig. 4).

The shrinkage cracks seen on surfaces of clay which have dried in the sun frequently subdivide the clay into hexagonal plates. If the clay is homogeneous and of considerable thickness, say 10 to 15 feet, the shrinkage cracks extend downward and break up the mass into a series of columns. Although the amount of shrinkage in the case of clays is much greater, the action is identically the same as in the case of a solidified lava flow or an intrusive dike or sill.

Platy structure (jointing or parting) is due to the contraction, during cooling, of a molten rock whereby joint planes are developed parallel to the cooling surface. Thus in a horizontal lava flow this

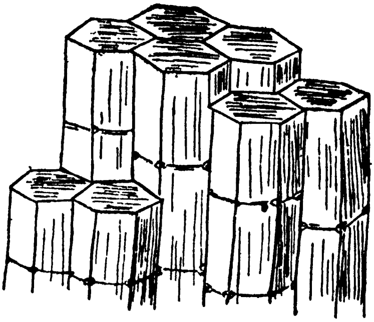


FIG. 4.
Prismatic jointing in basalt.

jointing would be tabular, because the contraction during cooling is vertical. In a vertical intrusion these planes of parting will be vertical owing to the contraction while cooling being horizontal between the enclosing walls.

If, on the other hand, a uniform mass of unconsolidated material is subjected to enormous pressure, it will be compressed and occupy a

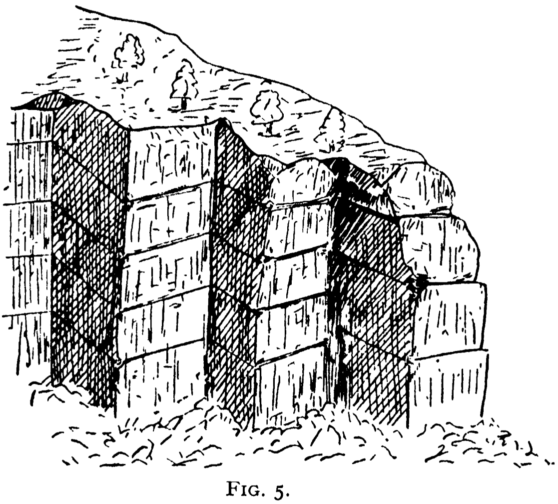


FIG. 5.
Joints in massive rocks.

smaller volume, and joint planes will develop at more or less regularly-spaced intervals (see Fig. 5). These joint planes, usually three in number and at right angles to each other, divide the volume of the
smaller volume, and joint planes will develop at more or less regularly-
rock into cubical or rectangular blocks. If the strata are laminated or in thin beds, the tendency is for the bedding plane to act as a joint

plane, and the resulting blocks have the shape of slabs. Occasionally a sedimentary bed having practically no lamination is, while in a moist condition, covered by a great thickness of molten lava. Sometimes the lava forces its way as an igneous sill below the massive bed of sedimentary material of more or less homogeneous composition. In these circumstances there is a tendency for the contained moisture in the thick sedimentary bed to be driven out, with the result that pressure exerted on the stratum is reinforced by the tendency of the material to shrink by de-hydration. In these circumstances it is not unusual to find a columnar structure developed in the sedimentary bed.

Should the partially consolidated material be finally forced down to a great depth in the crust of the earth and exposed to moderately

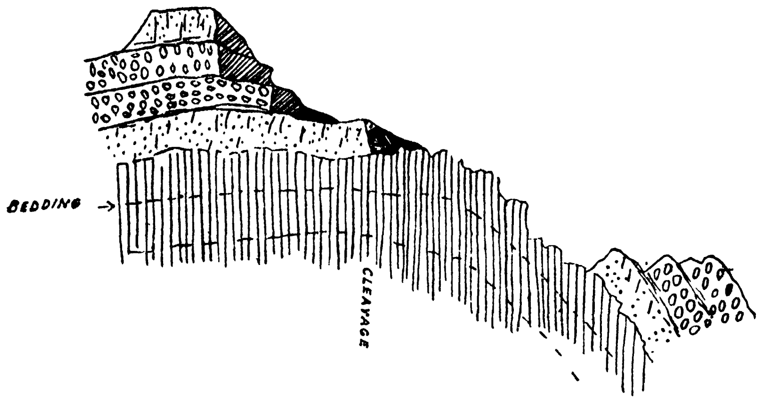


FIG. 6.
Cleavage due to Pressure.

high temperatures under immense pressure, a further diminution in volume will possibly occur. The component mineral particles will not only pack more closely together, but their molecules will do the same and re-crystallise as denser minerals, and thus produce heavier and more compact rocks. This diminution in volume under pressure induces a condition of strain which is only relieved by the production of divisional planes of weakness, such as joint planes or cleavage (see Fig. 6).

As previously stated, advantage is taken of the joint or cleavage planes in the process of quarrying—the shape and size of the blocks, slabs, or columns of stone extracted naturally depending on the distance apart of the joint planes and the type of rock concerned. In various parts of the world—Egypt, Mexico, Chile, India, etc.—there are found ancient monuments and the ruins of great buildings which have been constructed of the practically undressed blocks originally quarried. The Pyramids of Egypt call for no special remark in this connection, except that they indicate a condition of leisure to which we are un-

accustomed. However, when we find their bridges built of undressed stone, our interest is aroused at the ingenuity displayed by those early engineers.

" One such bridge was constructed over the south branch of the River Kaveri near Seringapatam, probably at a period dating before the usual construction of arch work. A portion of the bridge serves as an aqueduct to convey water from the river to the town. The structure is of the rudest kind. 'Square pillars of granite are cut from the rock, of a sufficient height to rise above the water at highest floods. These are placed upright in rows, as long as the width of the bridge, and distant about 10 feet from each other. They are secured at the bottom by being let into the solid rock, and their tops being cut level, a long stone is laid upon each row. Above these stones others are placed contiguous to each other, and stretching from row to row in the direction of the length of the bridge.' The celebrated bridge over the Euphrates at Babylon was constructed on similar principles." (See "Ways and Works in India," by G. W. Macgeorge, 1904; also Mill's "History of British India.")

The following extracts from Hatch and Rastall's book ("Text Book of Petrology," Vol. II, "The Sedimentary Rocks," 1923) are worth quoting at this point. They say, p. 280:

" The cleavage of metamorphic rocks must be carefully distinguished from the cleavage of minerals. It is unfortunate that this word is used to designate two essentially different things; for the former is a secondary character, superimposed by pressure, whereas the latter is a property inherent in the mineral, and is in no way dependent on pressure." And further on, p. 282, that "cleavage is nearly always associated with strongly marked folding; in fact the cleavage of sedimentary rocks does not begin, as a rule, till compression and folding have reached their limit. Since the compressibility of different rock types varies very widely, the combined folding and cleavage of heterogeneous rock masses produces some very curious and complicated effects."

Consolidated and calcareous rocks do not undergo compression to any appreciable extent. Argillaceous rocks are very compressible, and consequently cleave with readiness owing to the development of cleavage planes. These planes of weakness may not be clearly visible in fresh, undecomposed rocks, though they are evident in weathered specimens; they can, however, be utilised in quarrying rock.

The general opinion to-day is that the cleavage planes of slates are due to great mechanical forces which have compressed the clay or shale substance at right angles to the plane of cleavage. Tyndall illustrated this effect by the following experiment—a piece of fine white wax which had been previously well kneaded was pressed and worked between two wet pieces of glass, and, as a result, the wax became

"easily separable into plates with flaky sides, just like a piece of newly split slate rock." (D. C. Davies, "A Treatise on Slate and Slate Quarrying," 1878, p. 17. Crosby Lockwood.)

The development of cleavage in the arched portion of a fold is not uncommon and clear evidence is obtained that the pressure is normal to the cleavage planes. It is seen that the cleavage is parallel to the axis of folding, and it is an accepted fact that the axes of folds are at right angles to the direction of pressure. Generally, the pressure is horizontal and the folds form the orographic axes of mountain regions. These folds are frequently found in a "pushed over" or over-fold condition, and in some cases thrust faulting may result in the fold becoming more or less horizontal. A local subsidence or uplift may finally produce true horizontality. These extreme cases of folding are found in areas of ancient mountain chains, such as the Aravallis of Rajputana.

It has been found, when other conditions are similar, that the texture of a rock affects the distances between successive parallel joint or cleavage planes. In coarse-grained granites the individual blocks which can be obtained from one group of joints may be of gigantic size. Enormous slabs have often been quarried from hard, coarse-grained, massive sandstones. It is difficult to obtain very large blocks from quarries in fine-textured rocks, such as basalt, quartzite, and some marbles. The thin sheets of very fine-textured clay rock, known as slate, are familiar enough to all engineers.

There are usually three sets of joints or parting in all rock masses. In most rocks the three sets of divisional planes are, more or less, at right angles to each other. If the rocks are bedded, as in the case of the sedimentary rocks, the bedding plane will function as one plane of parting. When such beds are tilted, the joint planes may be vertical, and therefore oblique to the inclined bedding plane. In the case of beds which dip at various angles, one set of vertical joint planes generally occur parallel to the strike of the beds and are called "strike joints"; a second set of vertical joint planes, usually not so well developed, cut the beds in the direction of their dip, and are called "dip joints." Cases occur, particularly where the strata have been severely buckled and compressed, in which the strike and dip joints are absent and two sets of diagonal joints are present. If these rocks have been subjected to intense compression, it may be impossible to obtain large-sized blocks for building purposes, because, although large pieces may be quarried, they break up too easily when handled and trimmed.

In the excavations of the Panama Canal it was found that jointing and fissuring, chiefly due to shrinkage and earth-movements, caused

most of the smaller masses of igneous rock to break out in very small pieces when blasted.

"In getting crushed rock (rhyolite) from Ancon Quarry, this feature saved the United States hundreds of thousands of dollars in blasting and crushing costs. Lack of such fissuring was one of the reasons why the rock (andesite) at Porto Bello was more expensive to blast and crush. The coarse breaking quality of the Porto Bello rock, however, was useful in furnishing strong and heavy material with which to armour the breakwater against sea waves." (See "Outline of Canal Zone Geology," by Donald F. Macdonald, Trans. International Engineering Congress, 1915, p. 77.)

GEOLOGICAL MAPS.—If the surface of a country was stripped of all vegetation and soil and the rock laid bare, it would be possible, with sufficient expenditure of time and money, to colour the different kinds of rock in a distinctive way, *e.g.* sandstones, yellow; shales, grey; limestones, blue; granites, pink; dolerates, green, etc., and to mark the position of inclined strata and other structural details with suitable signs. An observer in an aeroplane, looking down on such a surface, would see a real geological map.

An ordinary map, with the topographical features clearly shown, forms the basis of a geological map. On it the geologist marks the position of the out-crops, dips, faults, etc., of the rocks which occur in the area of the map. If the geological details are intricate, he requires a larger scale map, just as an engineer would do to show the contours of a reservoir basin. If the direction and degree of the dips and faults, etc., are accurately delineated, the map will serve as a plan from which cross-sections can be constructed. By so doing, it is possible to depict the solid structure of the rocks of any area, and, *vice versa*, by studying a geological map and geological sections, it should be possible to obtain an idea of the structure of the country.

The geological maps published by the Geological Survey of Great Britain are of two kinds—Solid maps and Drift maps. The former type resembles the map described in the preceding paragraph: they do not show superficial accumulations such as glacial drift, etc. In the latter type of map these omissions are inserted. Drift maps are of importance in surface works—such as reservoir sites, the location of dams, etc. Solid maps are useful in questions of mining, boring, etc., when the work lies some depth below the surface.

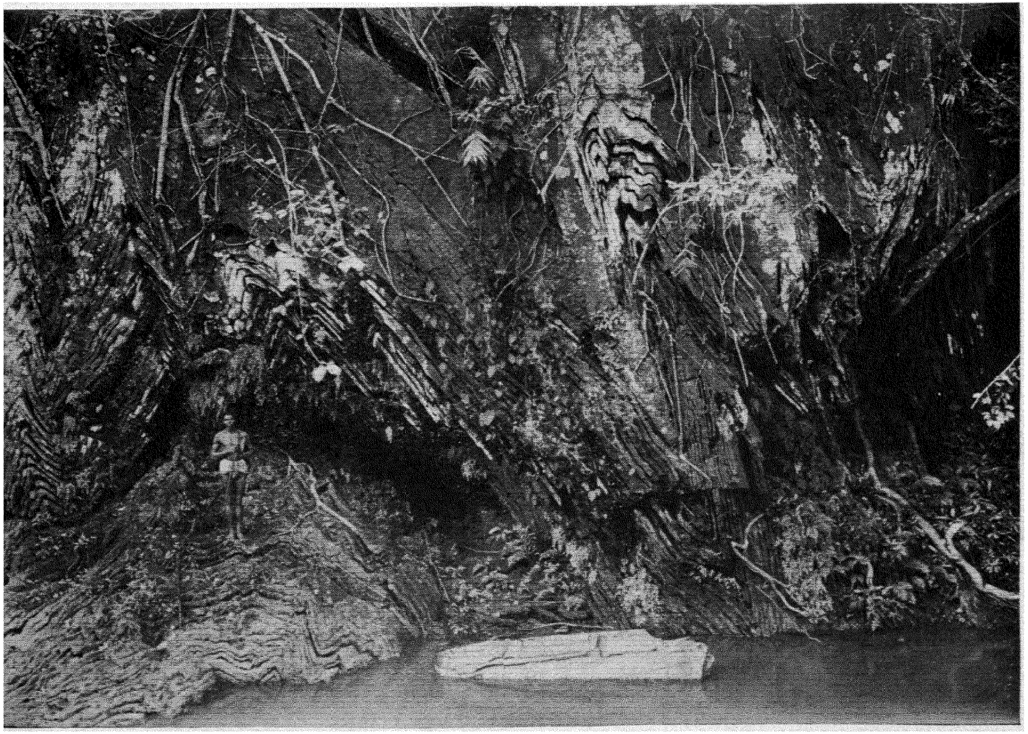
There are certain details shown on carefully prepared geological maps from which it is possible to draw correct conclusions regarding the geological structure, in the same way as an engineer can read the surface features of a country from an accurate topographical map. For example, when contour lines are seen close together on a topographical map, it is safe to infer that the slope of the ground is steeper

there than in an area where the contours are further apart. Similarly, on geological maps gently inclined strata show wide out-crops on level ground and narrow out-crops on steep slopes. The out-crops of horizontal beds will curve into the valleys with the contours; also beds which cross a valley transversely and dip upstream will have in-baying out-crops. If these out-crops extend far up the valley, it means the strata have gentle dips. On the other hand, if the in-baying is slight, the inference is that the beds are dipping at a high angle. Should the out-crops cross the valley in straight lines, it is obvious that the strata must be vertical. When the out-crop of a group of beds is represented by a V, with the point of the V down the valley, it is generally safe to conclude that the strata are dipping down-stream. If the beds cross a valley obliquely or are folded, irregular out-crops will be shown.

For reasons of uniformity in the production of geological maps, it is best to choose the same colours for representing rocks, and the same symbols or signs for indicating dips, etc., as have been adopted by the Geological Survey of the country in which investigations are being made. The index of colours and signs is always attached to a geological map, as it forms a key to the interpretation of the map.*

An engineer is often able to lay down the general alignment of a railway on a good topographical map without having previously gone over the ground. Similarly, with an accurate geological map, it is possible for a geologist to estimate the depth at which certain beds of rock may be encountered in sinking a well. The making of maps and the drawing of sections are so essential a part of the engineer's work that he will seldom have any difficulty in reading a geological map. Also, if he is familiar with the common rocks, and can unravel the structure of an area, he will, with his greater experience, be able to produce a very neat, mechanically correct, geological map.

* *N.B.*—Dr. Gertrude L. Ellis has written an excellent little work on the subject: "The Study of Geological Maps" published by the Cambridge University Press in 1921.



Per favour D. G. S. I.] CLOSELY FOLDED STRATA. [*Photo by H. C. Jones, Esq.*

Quartzite hematite beds, although very hard and somewhat brittle, as found to-day, show that they behaved almost as plastic material under the conditions of folding.

To face page 70.

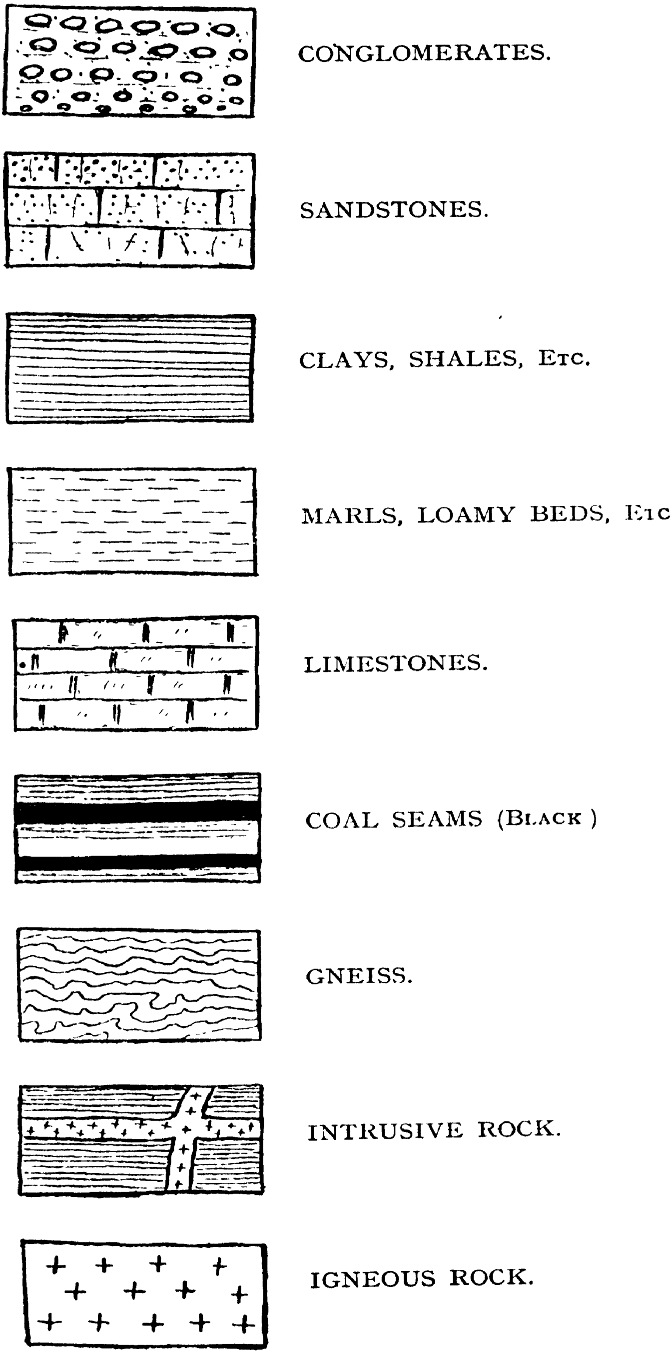


FIG. 7.
Geological Index.

CHAPTER V

THE PHYSICAL CHARACTERS OF ROCKS

THE most important physical characteristics of rocks which are required for engineering purposes are their durability, hardness, toughness, porosity and strength. These properties are dependent on the mode of occurrence, type, and condition of the rocks, and are modified by their subsequent treatment when exposed to the solvent action of acid or salt waters, great changes of temperature, and when subjected to mechanical pressure, abrasion or impact.

DURABILITY.—Rocks, as previously stated, are

" for the most part composed of minerals, and minerals for the most part are definite chemical combinations which are only, as a rule, permanent under stable conditions. If the minerals are submitted to new conditions, quite different from those under which they were formed, with new chemical and physical factors operating on them, they will tend to change into other minerals, that is, to turn into new chemical combinations, which will be most stable under the new conditions." (See " Rocks and Rock Minerals," by L. Pirson, p. 333.)

Those igneous rocks, whose constituents have rapidly crystallised and cooled from a highly-heated liquid condition, are particularly liable to undergo paramorphism or decomposition. Numerous cases are known in which dolerites have gradually changed to epidiorites as a result of the augite being converted into green hornblende. The peridotites are well known for their alteration to serpentine, and even into clay-like masses, owing to the instability of the mineral olivine.

The sedimentary rocks seldom suffer a metathetical re-distribution of their constituents. Sandstones and shales, under considerable pressure, become compact quartzites and slates, respectively; they suffer no chemical or mineral change, and are therefore relatively durable rocks. Marble is a more compact stable form of limestone, but, owing to its comparative softness and solubility, it is liable to weather badly under certain conditions.

The most stable minerals in the upper zones of the earth's crust appear to be quartz, hornblende (amphibole), albite (felspar), and biotite (mica); consequently, on theoretical grounds, some granites, hornblende syenites, diorites, epidiorites, and similar rocks, including

certain metamorphic rocks and the sedimentary varieties already mentioned, should be the most durable types. They are durable from the point of view of mineral stability when exposed to normal weathering influences.

HARDNESS.—This physical characteristic depends, partly, on the hardness of the component minerals of the rock and the cohesion between the several particles which compose the rock. Fine-grained granites, owing to the presence of quartz grains, are usually harder than any other type of igneous rock, although they are not as hard as quartzites with a cementing matrix of secondary silica. Sandstones, without any cementing matrix, are friable rather than soft, because the loosely-held grains of quartz are rubbed off the surface of the stone. Pure marbles are relatively softer than dolomitic marbles, because calcite is softer than the magnesian carbonate, magnesite.

ABRASION TESTS.—Experiments made by Mr. E. T. Lovegrove (*The Surveyor*, November 5, 1897, and December 14, 1900).

No of different specimens	Material	Mean percentage of wear		
		Chips	Dust	Total
6	Granite	1.00	9.15	10.15
2	Syenite	0.66	3.98	4.64
4	Whinstone (Andesite) ..	0.87	16.45	17.32
3	Basalt	1.33	26.34	27.37
3	Limestone Kentish rag magnesian carboniferous	2.19	22.23	24.42
1	Sandstone (Pontypridd) ..	0.00	27.54	27.54
3	Quartzite	0.06	4.84	4.90
8	Flints (a)	3.09	9.50	12.59
3	Flints (b) (same stones as (a) after being worn)	0.93	3.91	4.84
2	Slag (iron)	0.61	14.37	14.98

Four lbs. of broken stone, cubes about 2½ inches, were placed with half a gallon of water in a cylinder 11½ inches internal diameter, and subjected to 8,000 revolutions at a speed of 20 revolutions per minute, equal to 4½ miles.

The cylinder had three 1-inch angle irons projecting on the inside face to give impact.

TOUGHNESS.—Toughness is best described as resistance to impact. This property depends on the interlocked condition of the mineral constituents and on the individual tenacity of the minerals.

Interwoven needles and plates of hard, slightly elastic minerals will form an exceedingly tough rock (see Photomicrograph No. 8). This inter-penetrating structure of epidiorites, diorites, and dolerates makes them particularly suitable for road metal and paving setts. An interlocked, granular texture (see Photomicrograph No. 14) is also capable of producing a tough rock, if the individual grains are irregular, as in many granites, and not rounded as in most quartzites. Sandstones are not tough, because the grains are not only rounded, but generally uncemented. The easy cleavability of calcite prevents marbles which have an interlocked granular texture from being tough (see Photomicrograph No. 11).

POROSITY.—It is best to estimate the porosity of a rock by the difference in weight of a specimen which has been soaked in water for 24 hours, under a hydrostatic head of 30 or 40 lbs., and then dried for the same time at 105° C. The ratio of the volume of the water given off in drying to the total volume of the rock represents the porosity.

Rocks which have an interlocked texture, such as the igneous rocks, marble, most quartzites, and nearly all the gneisses and schists, have practically no porosity and are consequently impervious. The sedimentary rocks, *e.g.* sandstones, clays and limestones, contain a large volume of pore-space—in some cases as much as 20 to 30 per cent. of the total volume of the rock. The pore-spaces in sandstones and chalk are relatively large and do not offer considerable resistance to the movement of water through them; such rocks are said to be porous. On the other hand, the interstices in clays and soft shales are exceedingly small and offer great resistance to percolating water; consequently, these rocks, although possessing considerable porosity, are impervious.

STRENGTH.—The word strength as applied to a rock is not always used in the same sense; it usually refers to the ability of the rock to withstand crushing under direct pressure, as in blocks and columns, and sometimes refers to the resistance to fracture by transverse loads on stone beams. Many factors govern the strength of a given rock—the behaviour of the mineral constituents when exposed to atmospheric agencies, acids and salt water, frost, heat, moisture, etc.

The strength of stone beams can be roughly estimated from the details given in the table on the following page.

From the tables given it would appear that the igneous rocks, with their interlocked mineral components and absence of interstitial space are, in general, stronger than the sedimentary types; while the metamorphic rocks, the gneisses and schists, quartzites, slates and marbles, etc., occupy an intermediate position in the scale of strength.

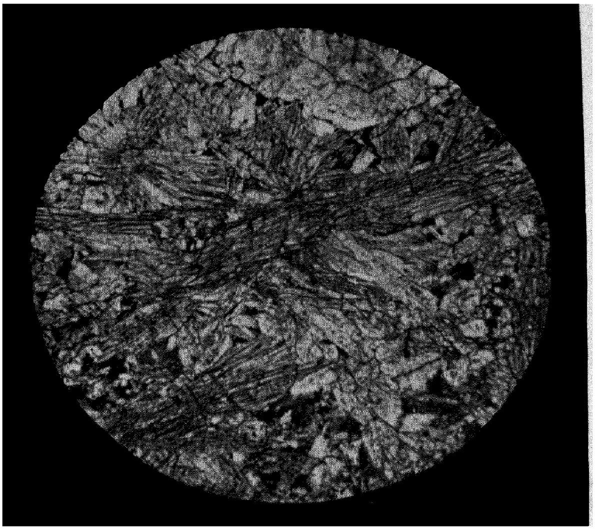


PHOTO-MICROGRAPH 17.
Fibrous sillimanite (massive). This is one of the toughest materials known. It is practically immune to heat. (× 25.)

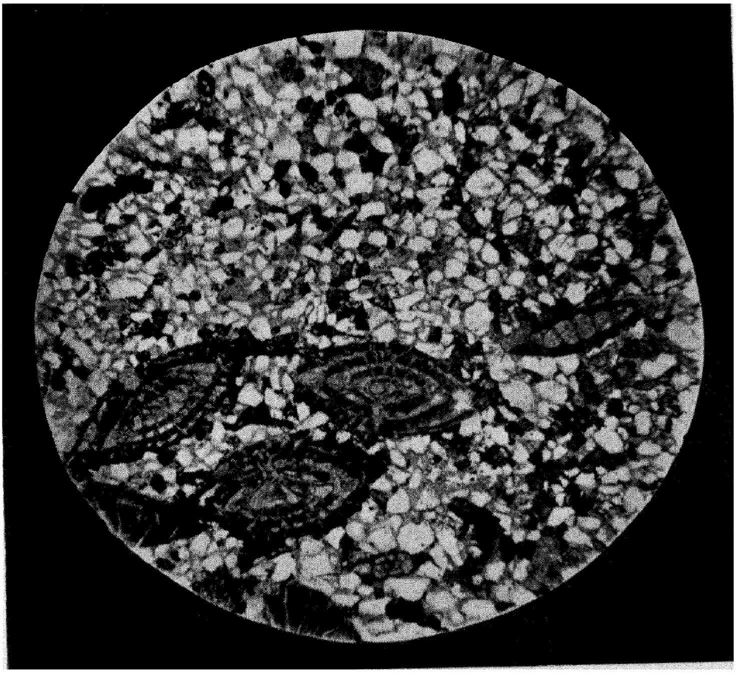


PHOTO-MICROGRAPH 18.
Nummulitic sandstone. Showing sections of the fossil, nummulites, in a matrix of fine grained quartzite. Specimen from British Garhwal. (× 25.)

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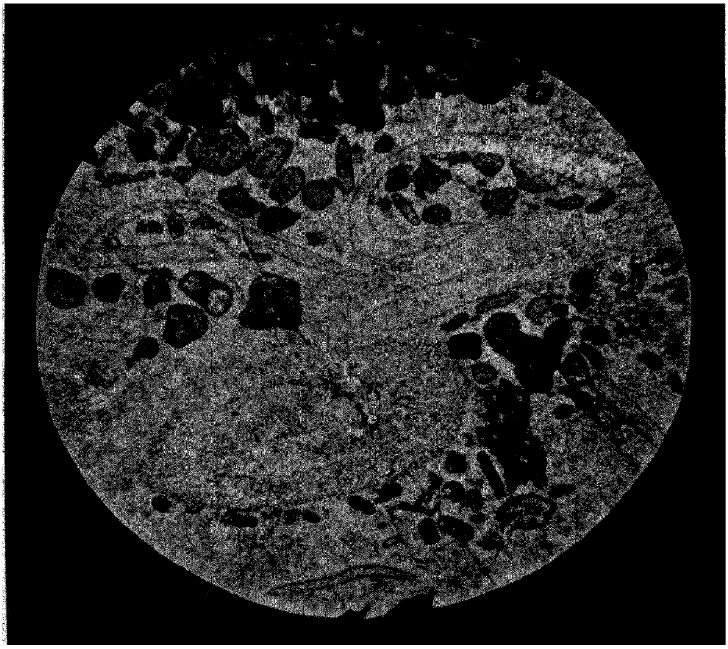


PHOTO-MICROGRAPH 19.
Fossiliferous limestone. Showing a fossil limestone containing unidentified brachiopods. Obtained from a limestone conglomerate at the entrance to the Khyber Pass near Jamrud. (× 25.)

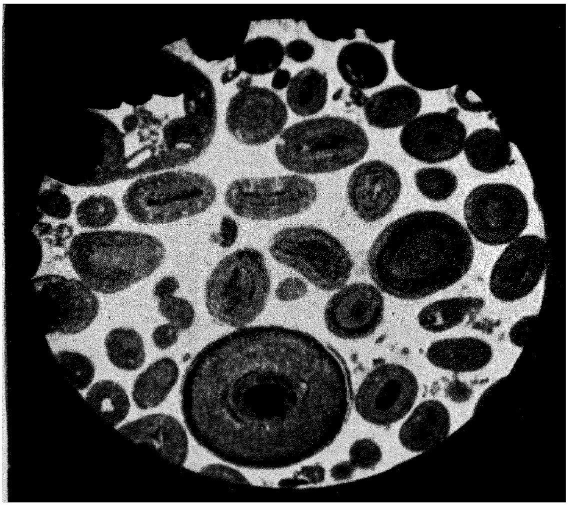


PHOTO-MICROGRAPH 20.
Oolitic limestone. The oolitic texture of the oolitic limestone from Leckhampton Hill, near Cheltenham. (Miss M. E. Biden.)

[*To face page* 75.

STONE BEAMS (Good Building Granite)

Depth in Inches	Clear Spans in Feet.											
	1	2	3	4	5	6	7	8	10	12	15	20
	Safe Centre Loads in Pounds.											
7	10	5	–	–	–	–	–	–	–	–	–	–
2	40	20	13	10	–	–	–	–	–	–	–	–
3	90	45	29	21	17	–	–	–	–	–	–	–
4	160	79	52	39	31	26	21	–	–	–	–	–
5	250	124	82	61	48	40	34	–	–	–	–	–
6	360	179	119	89	70	58	48	42	32	–	–	–
7	490	244	162	120	96	79	67	58	45	36	27	16
8	639	319	212	158	126	104	88	76	59	47	36	22
10	999	499	231	248	197	163	139	120	94	76	58	38
12	1,439	718	478	357	284	236	201	174	137	111	85	53
14	1,959	978	650	487	388	322	274	238	188	153	118	81
16	2,559	1,278	850	636	507	421	359	312	246	201	157	109
18	3,239	1,618	1,077	806	643	534	455	396	313	257	200	141
20	3,999	1,998	1,329	995	794	660	563	490	388	319	249	176
22	4,839	2,417	1,609	1,205	961	800	682	594	470	387	303	216
24	5,758	2,877	1,916	1,434	1,145	951	813	708	562	463	362	260
27	7,288	3,642	2,425	1,815	1,450	1,205	1010	898	713	588	462	332
30	8,998	4,496	2,995	2,243	1,791	1,489	1,273	1,110	882	728	573	415
33	10,888	5,441	3,624	2,714	2,168	1,803	1,542	1,345	1,069	883	693	505
36	12,958	6,776	4,314	3,231	2,581	2,147	1,936	1,603	1,275	1,054	832	606

N.B.—If uniformly distributed over the clear span, the safe extraneous loads will be twice as great as those in the table. For good slate on bed the safe loads may be taken at about 3 times; for good sandstone on bed at about $\frac{1}{2}$; and for good marble or limestone on bed at about the same as those in the table. *Factor of Safety taken*—1/10 *Breaking load.*—Trautwine's Pocket Book, 1907, p. 924.

It is, however, well known that many slates, schists, etc., are superior in transverse strength to most igneous rocks.

In all types of rocks the medium-textured varieties are strongest. The weaker minerals in coarse-textured rocks usually crush, and by so doing involve the strength of the whole rock. The fine-textured varieties, on the other hand, appear to possess less cohesion between the particles.

In the following table the average crushing strengths of various kinds of undecomposed rock, etc., are given:

CRUSHING STRENGTH OF BUILDING STONE.*

	Average tons per sq ft.
Coarse, porphyritic granites	700
Medium-grained granites	1,000
Fine-grained granites	800
Doleritic basalts	1,000
Epidiorites and diorites	1,500
Sandstones, coarse, hard	600
Sandstones, medium to fine, hard	400
Marble, coarse to medium	800
Marble, fine to medium	300
Limestones, hard	400
Limestones, soft or oolitic	100
Slate, fine, hard	800
Clay-slate, hard	600
Clay-slate, normal	400
Brick, good	170
Cement	100
Concrete, 6 to 10 months old	75
Cement mortar	65
Brickwork, in good cement	50
Lime mortar	40
Brickwork, ordinary	25

N.B.—The pressure is applied perpendicular to the plane of foliation, bedding, or lamination. Stones generally begin to crack or split under about half their crushing loads. In practice, neither stone nor brickwork should be trusted with more than 1/6 to 1/10 the crushing load, according to circumstances.

EFFECT OF MOISTURE ON STRENGTH.—As a result of tests carried out in the United States in 1890 (at Watertown Arsenal), it was found that after alternate drying and soaking (at 100° C.) the crushing strength of the wet rock was usually considerably less than that of the dry rock. For example, the strength of

Granite became 0.837 of its original value;

Sandstone became 0.669 of its original value;

Limestone became 0.588 of its original value;

Marble became 0.462 of its original value.

* Fresh undecomposed specimens only.

Rock.	Porosity per cent.	Crushing strength in lbs per sq in.		Co-efficient of Thermal Expansion per 1° C.	Stress produced by 1° C. Rise in temperature in lbs. per sq. in.	Specific Heat Calories per gram.
		Dry.	Wet.			
Fine-grained yellow sandstone (Millstone Grit)	12	8,480	8,280	0.0000123	0.210	0.193
Fine-grained red sandstone (Permain)	15	2,520	2,510	0.0000099	0.473	0.178
Soft Keuper sandstone ..	16.6	900	400	?	–	–
Hard Keuper sandstone ..	17.7	2,020	1,750	0.0000135	0.121	0.189
Compact quartzite	2.9	3,680	3,660	0.0000162	0.196	0.225
Compact limestone (freestone)	20	1,570	600	0.0000035	0.204	0.196
Bath (oolitic) limestone ..	17.8	1,140	770	0.0000048	0.141	0.170
White Carrara marble ..	0.78	4,450	4,400	0.0000087	0.857	0.204
Red rouge royal marble ..	0.93	6,420	4,500	0.0000058	0.670	0.200
Black Dinant marble	0.73	6,710	6.700	0.0000049	0.147	0.199
Red Peterhead granite ..	0.28	5,480	5,200	0.0000102	0.513	0.185
Grey Aberdeen granite ..	0.12	5,950	5,940	?	–	0.166
Green Diabase (dolerite) ..	0.24	6,070	6,030	0.0000097	0.731	0.181

Later investigations (see "Physical Properties of Building Stones," by Messrs. Baldwin-Wiseman and Griffith) (Paper No. 3856, *Min. Proc. Inst. Civil Engineers*, Vol. CLXXIX, 1907, p. 290) have shown that porous rocks are less affected than impervious rocks of the same porosity. It was thought that this was due to the water being more easily expelled from the larger pore-spaces of the porous rock. Interesting data, taken from the above-mentioned paper, are shown on the previous page.

INFLUENCE OF HEAT.—The coefficients of thermal expansion (linear) of the various rocks discussed in the above table are also included in that table. Other determinations of the linear coefficient of thermal expansion are available. One of these (see Adie, in *Trans. Roy. Soc., Edin.*, Vol. XIII, p. 366) is particularly interesting, because it shows how the presence of moisture in a rock may seriously increase the coefficient of thermal expansion. Much, of course, depends on the porosity, mineral composition, coarseness of texture, etc., of the rock. The following examples of well-known rock make this clear. The coefficients of red Peterhead granite when dry = 0.00000498 per 1° F.; when moist = 0.00000532 per 1° F. Corrennie granite (red variety) when dry has a constant = 0.0000057; and in grey Aberdeen granite, when dry, 0.00000438. Similarly, the coefficients of (linear) thermal expansion of sandstones vary greatly, from 0.00000953 in quartizitic types to 0.0000051 in soft sandstones. Slates have an average coefficient of thermal expansion equal to 0.00000576 when dry; the coefficient value may, however, vary from over 0.0000063 to less than 0.0000044 in certain classes of slate. The constants for various kinds of marble are nearly as variable as in sandstones—in some Sicilian varieties (white) the value is 0.0000078 when the stone is moist, and 0.00000613 when dry. For Carrara marble the following values have been determined: 0.00000662 when moist and 0.00000363 when dry. The coefficient of thermal expansion of black Dinant marble is stated to be as low as 0.000002 per degree when dry. The average value of the coefficient of thermal expansion for dolerite, diorite and "trap" rocks, in general, is estimated to be, roughly, 0.00000449 per 1° F. (In comparing the values given above with those in the preceding table, it is to be remembered that the figures given in the table are per 1° C., whereas these are per 1° F.)

In the chapter on rock-forming minerals, attention was drawn to the possibility of internal strain being developed in certain rocks subjected to great variations of temperature.

An excellent example of the poor fire-resisting properties of a rock containing minerals of widely different coefficients of thermal expansion is to be seen in London in the granite masonry at the base of

Nelson's Monument in Trafalgar Square. On Armistice night (11th November, 1918) huge bonfires were lit by rejoicing crowds in various parts of the square. Fortunately, the authorities intervened in time; but the effects of two of these fires can be seen in the disfigurement they caused. Even to-day (1934) the steps at the base of the column facing Cockspur Street are seen to be damaged, and the scaling of the plinth wall between the lions on the Whitehall side is plainly visible.

It is doubtful if the sandstone monoliths of Stonehenge would have survived the lapse of centuries if they had been erected in a dry tropical climate subject to a diurnal range of temperature of 40° F. Photograph 3 shows a block of granite which has been split by the heat of the sun. The practice of fire-setting and splitting for the quarrying of granite and other rocks is still carried on in many countries.

"Every day's variation of temperature adds its quota of disintegrating action on the granite rocks: blocks are split asunder, and crystals of felspar and quartz are broken into sand and slowly removed by gravity and wind. . . .

"Reference may be made to the huge cracks on Jebel Garro (34 kilometres West of Aswan) . . . the diurnal temperature-range is a sufficient explanation for the facts observed. Thirty-six thousand times in a century the rock has gone through a cycle of expansion and contraction; a crack once started on the surface, the successive slight opening and closing of it would soon deepen it, and ultimately cut right through the thick bed, leaving a great detached mass of limestone on a more or less sloping stratum of clays. Then the continued operation of expansion and contraction of this detached mass would cause it, under the influence of gravitation, to move slowly away from its parent rock . . . a block of limestone 10 metres in length subject to an average diurnal change of only 1° C. would in this manner creep through a distance of a metre in 55 years. In the case of sandstone masses, the movement would be at least twice as rapid, owing to their greater coefficient of expansion." (See "A Description of the First or Aswan Cataract of the Nile," by John Ball, Ministry of Finance, Survey Department, Egypt, 1907, p. 112.)

THERMAL CONDUCTIVITY.—Professor Henry Briggs, in his paper on "Spontaneous Combustion and Heat through Crushing" (see *Colliery Guardian*, Vol. CXXIV, 1922, p. 1226) gives data with regard to various rocks as shown on the following page.

He states that in crushing hard rocks suddenly and finely there is likely to be a considerable liberation of heat, while the rise of temperature resulting from crushing coal measure shale is about 50 per cent. greater than that due to comminuting average bituminous coal under the same conditions. Cases are known in which carbonaceous shale is more subject to spontaneous ignition than coal in the vicinity.

Rock	Heat Conductivity C.G S. units.	Specific Heat
Coals, Newcastle (bituminous)	0.00068	0.2 to 0.4
,, Cannel	0.00120	
Coal measure Shale ..	0.00235	0.18 to 0.23
Slate with cleavage	0.00561	0.21 to *is*.207
,, across cleavage	0.00391	
Carboniferous limestone ..	0.0055	0.217
Magnesium limestone	0.00522	0.245
Hard Sandstone	0.00672 (Carboniferous	
Soft Sandstone	0.00486 sandstone)	0.22 to 0.29
Quartzite	0.00954	
Mica Schist	0.0052	
Gneiss (German)	0.00514	
Basalt	0.0052 to 0.0056	0.20 to 0.205
Granite	0.0058	0.192 to 0.198

However, as stated by other authorities, it is not so much liberated heat as the fineness of the grinding in the presence of air that causes the ignition of the carbonaceous material by oxidation.

The differences of thermal conductivity in various rocks are of greater interest to the physicist than to the engineer, because it is doubtful if the coolness of a house, even in a hot, sunny country, would be affected as much by the choice of building stone as it would by the thickness of the walls, etc.

ELECTRICAL CONDUCTIVITY.—The electrical conductivity of various mineral substances is of particular value in some branches of engineering. The choice of marble or slate for switch-board panels necessitates an investigation of the electrical resistance of these stones. When perfectly dry, all rocks, from hard granites to the finest sand, have exceedingly high ohmic resistance (upwards of 100,000 ohms per cubic foot) ; the resistance falls when the material becomes wet ; consequently, materials of a high degree of porosity, *i.e.* the sedimentary rocks, are, in general, not suitable for the purpose of making electrical switch-board panels ; the igneous rocks and several metamorphic rocks—marbles, slates, and sandstones—are suitable, if free from cracks or veins of metallic minerals ; marbles and slates are usually chosen because of their uniformity of colour and the ease with which they can be manufactured into slabs.

The greater the electrical conductivity of a rock used for building purposes, the greater the protection afforded to the interior of the building from lightning. Sir Oliver Lodge has said that a metallic covering (top, sides, *and bottom*) ensures perfect safety from lightning

to the space within the metallic cage. If, however, the floor or large spaces on the sides (doors, etc.) are unprotected, there is danger of lightning entering the space; this danger is increased if an insulated conductor is led into the building.

ELECTRICAL RESISTANCE.

	Resistance in ohms per foot cube of Wet Stone.
Millstone grit	660
Permian sandstone	580
Hard Keuper sandstone	1,160
Quartzite	14,300
Limestone	1,430
Bath oolite	930
Carrara marble	8,450
Rouge royal marble	11,500
Black Dinant marble	4,790
Peterhead granite	12,100
Diabase	54,600

A method for searching for minerals—particularly iron ores—has recently been developed by the Erda Company of Gottingen (see *The Mining Journal* for 4th August, 1923, p. 599). The procedure is described as follows:

"At two points—electrodes as they are called—several miles apart, an electric current is sent into the soil. Normal conditions prevailing, the current will spread itself. . . . The equipotential lines at every point are rectangular to the flow of the current. . . . An ore body offering less resistance to the flow of the electric current than the surrounding soil will cause the current to concenrtate itself in the ore body. A distortion of the equipotential lines will result. The apparatus consists of two iron rods, a telephone connected to the rods by a wire, and an ingenious device for intensifying the sound heard in the telephone. One of the rods is stuck in the ground and the other shifted about until no sound is heard in the telephone receiver—the two rods will be on an equipotential line. The points thus found are marked on a map and the equipotential line constructed therefrom. The distortion of the latter gives a correct idea of the position of the ore deposit, the size and depth of which can be ascertained by the extent of the distortion. The energy necessary for investigating 200 acres is only 1–2 volts."

There is another aspect of the electrical conductivity of various rocks which affects the choice of sites for the erection of radio-telegraph stations. It is known that the nature of the surface of the earth between two stations considerably influences the strength of the signals. A conducting surface (salt water, *i.e.* the sea) allows the electro-magnetic waves to pass easily and without absorption. A non-conducting surface (hot dry sand—a desert) allows the waves to enter the rocky material, and they are, to some extent, absorbed by the

surface. Professor J. A. Fleming gives the following conductivities of various kinds of material and indicates the importance of water as a conducting medium (see "Nature," LXXXII, 1909, p. 141).

ELECTRICAL RESISTANCE.

	Specific resistance in ohms. per metre cube.
Mercury	0.000001
Sea water	1
Fresh water	100 to 1,000
Moist earth	10 to 1,000 *
Dry earth	10,000 upwards *
Wet sand	1 to 1,000 *
Dry river sand	Very large *
Wet clay	10 to 100 *
Dry clay	10,000 upwards *
Slate	10,000 to 100,000 *
Marble	5,000,000 *

MAGNETIC SUSCEPTIBILITY.—It is well known that various minerals, *e.g.* magnetite, pyrrhotite, etc., are strongly magnetic, and the discovery of deposits of iron ore by means of a magnetometer is a recognised method of prospecting. Such methods of surveying (*i.e.* by a magnetometer) have been very successfully used in proving deposits of iron ore in Sweden. The method consists in ascertaining the strength of the earth's magnetic field and the magnetic declination. Occasionally a reference occurs to the effect that certain rocks have been found to possess magnetic properties, but the subject has not been followed up as fully as it might. F. Mallet (" Memoirs Geological Survey of India," Vol. XXI, Part 4) found that the basaltic lavas of the dormant volcano of Barren Island in the Bay of Bengal distinctly influenced a magnetic needle, although he could not detect any magnetite in the hand specimens which he examined. A fragment of fresh dolerite picked up by me in the Chhindwara district of the Central Provinces proved not only to influence a magnetic needle, but to possess polarity.

This property of those rocks which might be used for building purposes naturally assumes an importance in special cases. Magnetic instruments in a physical laboratory constructed of such material might give erroneous values for the earth's magnetic field, and other curious electrical phenomena, at present inexplicable, in test houses or power stations, may possibly be traced to the stone with which the house has been built.

MICROSCOPIC EXAMINATION OF ROCKS.—The occurrence of such names as trap, greenstone, whinstone, freestone, etc.,

* These materials owe their conductivity to interstitial water.

in our petrological vocabulary is evidence of the fact that the earlier geologists were not always able to identify immediately certain rocks which they had met with in the field. Even to-day petrologists frequently find it necessary to use similar non-committal and convenient field terms. In the case of coarse-grained rocks, such as granites, syenites, dolerites, sandstones and quartzites, shales and slates, limestones and marbles, gneisses and schists—varieties which constitute type specimens—there is seldom any difficulty in identification. On the other hand, there are a host of complicated rocks of fine-grained texture and peculiar association of not easily recognisable minerals, which cannot readily be identified except by an examination of thin sections under the microscope. Often, by a knowledge of its mode of occurrence, it is possible to make a shrewd guess as to the identity of a rock; but when a specimen is brought to a geologist, he may hesitate to give it a name. He may identify its mineral components and ascertain its chemical composition, and then make an approximate determination of the rock group to which it belongs. In the case of gneissose rocks, it is often impossible to say definitely whether the metamorphic form represents an original igneous rock or one of sedimentary origin. As the result of experience, the presence of certain minerals is now taken as indicating the origin of a rock found in a metamorphosed condition. The minerals staurolite, andalusite, sillimanite, etc., in a schistose rock are assumed as evidence indicative of an original sedimentary rock. The presence of talc, serpentine, hornblende, black mica, etc., are often assumed to be evidence that the gneisses and schists in which they occur were originally unaltered igneous rocks. These difficulties will soon become evident to the student of petrology when he endeavours to identify, without the assistance of a microscope, the various rocks he will encounter in the field.

Experience has taught us first to carefully note the mode of occurrence of a rock in the field, and then to recognise the various mineral components which are seen in the hand specimen. These observations, together with the colour, structure, texture, and specific gravity of the specimen, will provide preliminary data for identification. In the case of obviously igneous rocks, a reference to the rock classification will generally lead to a provisional determination, which can be verified later by the examination of a thin section under the microscope. Thus, suppose a massive intrusion of a coarse-grained, greenish-grey, granitoid-textured rock has been discovered, specimens of which are found to contain white felspar phenocrysts, dark green hornblende, and very occasional grains of quartz; a geologist may find some difficulty in saying whether the rock is a hornblende granite, a syenite,

or a quartz diorite. He will have to ascertain whether the felspar is orthoclase or plagioclase. This may not be possible in the field without the aid of a microscope. Under the microscope a glance will tell him whether orthoclase or plagioclase is present, and the interlocked texture will resolve any doubts regarding the true igneous character of the rock. If the felspar is orthoclase, he will probably not hesitate to call the rock a hornblende granite, provided quartz is common in the slide. If there is practically no quartz, he will call it a normal syenite. Should the felspar be plagioclase, he will write the rock down as a diorite. In the event of his discovering an appreciable percentage of augite present, he will class the diorite as belonging to the monzonite series of basic intermediate rocks.

In the case of obviously sedimentary rocks, there are usually fewer difficulties. The texture of the rock with the grains not interlocked, the presence of a cementing matrix, etc., help in ascertaining the origin of the rock, if its field associations are not known. An abundance of quartz grains will place the rock in the Arenaceous group. The shales and clays, whether ferruginous of calcareous, belong to the Argillaceous group. The limestones, whether containing fossils, or contaminated with siliceous or ferruginous matter, or having an oolitic structure, are classed in the Calcareous group. The superior general hardness of the Arenaceous rocks and the effervescence with acid in the case of the limestones are fairly safe determinative guides, should there be any doubt about the specimens. Difficulties arise when dealing with the finest-grained varieties of these rocks, especially when there is a considerable intermixing of the siliceous, argillaceous, and calcareous components.

When we turn to the metamorphic rocks, the presence of a foliated structure is the essential criterion for describing the rock as a gneiss. In the case of schistose rocks, there are no doubts involved in using the word schist, but when there is an entire absence of banding, foliation, or schistosity, some doubts may arise as to the metamorphic character of the rock. In the case of gneisses, we recognise such main types as granitoid gneiss, syenite gneiss, diorite gneiss, dolerite gneiss, etc., the mineral components being the same as in the unaltered rock. A marble having a foliated structure is commonly designated as a calc-gneiss. Slates and schists, in which the mineral staurolite is present, are known as staurolite schists, etc. Similarly, the word garnet may be used in designating garnetiferous gneisses and garnetiferous schists.

The discovery of a rock containing potash felspar (orthoclase), manganese garnet, and apatite is, however, calculated to leave the petrologist in a difficulty as regards its real origin and correct name. Dr. Fermor, while admitting that the rock is of metamorphic form, has

provisionally called it an igneous rock and given the specimen he found the name of kodurite. It is, however, difficult to find a name for a dark purple-green rock containing beautiful iridescent octahedra of magnetite in a matrix of green chlorite. The rock is of rare occurrence and obviously a metamorphic type. It probably represents the alteration of a dike of ultra-basic igneous rock.

The above remarks have particular reference to rocks which, although they may have suffered alteration, are not decomposed. As a rule, they are hard and firm, and the mineral components are fresh-looking. It is seen that these alterations are not due to decomposition which is effected by atmospheric weathering. Weathered rocks are generally soft or friable, and the felspathic minerals are nearly always hydrated; the ferruginous minerals are oxidized; there is an increased porosity of texture due to the presence of minute cracks and a loosening of the interlocked texture of the mineral components; soluble constituents have often been partially removed by percolating water; and the rock is generally lighter, and is very much weaker than its unweathered form.

The effects of weathering are usually evident in hand specimens, if considerable decomposition has taken place; but the microscope will detect that incipient degree of decomposition which may render the rock liable to be condemned for those engineering works in which strength and durability are of prime importance. The felspars are dull and cloudy, the mineral particles show interlaced cracks, and the mineral particles do not seem to interlock as well as they do in fresh unweathered specimens of the same type of rock.

MICROSCOPIC EXAMINATION OF ROCK SECTIONS.—From the remarks previously made with regard to the texture and shape of grains of the mineral components of various rocks, it is clear that the crystalline particles rarely show crystal outlines. Consequently, it is not always possible to identify the several mineral components with certainty, except by the laborious process of detaching individual particles and determining their specific gravity, refractive index, and other physical properties, and, possibly, having to make chemical determinations as well.

Much of this labour is saved by a microscopic examination of a thin section of the rock. The determinations are quickly made, and the results are frequently more reliable, and can always be checked without a repetition of the labour of procuring fresh samples for examination.

An engineer, who is familiar with the optical principles involved in the arrangement of lenses which form part of the telescopes used in the various types of surveying instruments, will have no difficulty

in understanding the construction of a petrological microscope. There is one feature which may be new to him; this is the so-called Nicol's prism for obtaining plane polarized light. Two Nicol's prisms are used: one, the polarizer, arranged below the stage on which the rock section is to be placed, and the other, the analyzer, inserted between the objective and the eye.

There are numerous books which describe the petrological microscope, and a detailed description is given in " A Text Book of Mineralogy," by E. S. Dana. The determinative manipulations are, however, better and more simply described in " Minerals in Rock Sections," by Lea McIlvaine Luquer (Van Nostrand, 1912). " Minerals and the Microscope," by H. G. Smith, second edition, 1919, price 5s., is also excellent.

Among other valuable books may be mentioned the " Manual of Petrographic Methods," by A. Johannsen, 1914 (McGraw Hill Book Co.); " Text Book of Petrology " (Vol. I, " Igneous Rocks," and Vol. II, " Sedimentary Rocks), by F. H. Hatch and R. H. Rastall, 1923 (Allen & Unwin); " Elements of Optical Mineralogy," by A. N. Winchell, 1922; " Petrographic Methods," by E. Weinschenk, and translated by R. W. Clark; and " Petrographic Methods and Calculations," by A. Holmes, 1921 (Murby).

It is to be understood that the engineer will make himself familiar with the elements of crystallography and the optical characters of the common rock-forming minerals which are grouped into one or other of the six crystal systems. However, for the sake of continuity, the following brief remarks may be found useful.

CRYSTAL SYSTEMS.—As will be seen in any work on crystallography, there are thirty-two mathematically possible types into which all crystal forms may be grouped (*i.e.* according to their planes, axes, and centres of symmetry. It has, however, been found practicable to group all known crystalline substances into one or other of the following systems:

(1) Isometric (Regular or Cubic) System. In this system are grouped those crystals whose faces or planes are symmetrical about three equal axes at right angles to each other. The common forms of this system are the cube, the octahedron, the dodecahedron, etc., and combinations of these.

(2) Tetragonal (Dimetric) System. The arrangement of the crystal faces are symmetrical about three axes at right angles to each other. Two of these (lateral) axes are equal, the third (vertical) is longer or shorter. The normal habit of the crystals is some form of square-sectioned prism, or pyramid, or a combination of these two.

(3) Hexagonal (Rhombohedral) System. This system has four

axes, three equal axes (lateral) in one plane intersecting at angles of 60°, and the fourth (vertical), at right angles to this plane, being longer or shorter. The usual forms of this class are hexagonal-sectioned prisms, and pyramids, and rhombehedra.

(4) Orthorhombic (Trimetric) System. In this grouping there are three axes (*a*, front to back; *b*, left to right; and *c*, vertical) at right angles to each other, but all of different lengths.

(5) Monoclinic System. This system has three axes (*a*, *b* and *c*) of unequal length. Two (*b* and *c*) are at right angles to each other, and the third (*a*) intersects one of the others (*c*) obliquely, but is at right angles to *b*. The plane containing the two axes (*a* and *c*) which intersect each other obliquely is a plane of symmetry. The third axis (*b*) is perpendicular to the plane of symmetry, and is a crystallographic axis.

(6) Triclinic System. This class includes all those forms in which there are three unequal axes (*a*, *b* and *c*) with all their intersections oblique.

Dana, in his Text Book, recommends the use of glass and wood models to illustrate various forms of the above six crystal systems. These models are readily obtainable.

Optical Characters.—It may be mentioned in passing that the grouping of the various crystal forms into the above Crystal Systems has a deeper significance than mere geometrical considerations, of equal or unequal axes intersecting at oblique or right angles, based upon mathematical laws. The lengths of the crystallographic axes are indicative of the fact that the velocity of light (refractive index), thermal and electrical conductivity, etc., are or are not equal in coincident directions through the crystals. Further, the perpendicular or oblique intersections to the crystallographic axes may be taken as indicating that the directions of maximum and minimum velocity of light through the crystals do or do not coincide with the crystallographic axes.

In the case of transparent or translucent crystals which belong to the Isometric System, light is transmitted equally in all directions; and were it not for the geometrical form, it would be difficult to distinguish such a mineral from certain other homogeneous substances, *e.g.* glass, opal, etc. Those substances which possess this homogeneous optical character are said to be ISOTROPIC—all crystals belonging to the isometric system are isotropic. They remain dark throughout a complete rotation of the section in which they occur when examined between crossed nicols.

Crystals of the tetragonal and hexagonal systems also appear isotropic when examined in a direction perpendicular to the plane con-

taining the equal axes, *i.e.* sections cut perpendicular to the vertical axis. This crystallographic axis is the only direction in which tetragonal or hexagonal crystals show no double refraction ; consequently, this axis is coincident with the only optic axis which such forms possess. For this reason tetragonal and hexagonal crystals are said to be UNIAXIAL. Sections of crystals of these two systems, if examined in any other direction, will show double refraction, and will transmit light and extinguish twice alternately if rotated through 360° when examined between crossed nicols. They are consequently ANISOTROPIC (not isotropic). If the straight-edged outline of such crystals is carefully observed when the section is rotated between crossed nicols, it will be seen that the mineral extinguishes when the cross wires (marking the plane of polarization of the nicols) are parallel with the straight edge of the crystal outline ; tetragonal and hexagonal crystals are, therefore, said to have STRAIGHT EXTINCTION. Practically all sections of Orthorhombic, Monoclinic and Triclinic crystals show the phenomenon of alternately becoming dark and light when viewed between crossed nicols while the section is in rotation. Sections perpendicular to an optic axis are rare, but these would show isotropic characters ; they are therefore all ANISOTROPIC. They have two, and only two, directions in which transmitted light does not suffer double refraction. These directions are known as optic axes, and for this reason all crystals belonging to these three systems, the Orthorhombic, the Monoclinic, and Triclinic, are said to be BIAXIAL.

Prismatic forms of the *Orthorhombic* system will give *straight extinction* ; *some sections* (those cut perpendicular to the plane of symmetry) of *Monoclinic* crystals will give *straight extinction* ; but, as a rule, *Monoclinic* crystals have oblique extinction ; and it is quite *exceptional* for *Triclinic* crystals to give *other than oblique extinction.* Straight extinction will only occur when the section is cut perpendicular to the plane containing the directions of maximum and minimum velocity of light —commonly spoken of as refractive index. The direction of intermediate velocity is perpendicular to the plane containing the other two. The plane which contains the directions of maximum and minimum refractive index also contains the optic axes. In orthorhombric crystals these directions of maximum, minimum, and intermediate refractive indices, which are always at right angles to each other, are coincident with the crystallographic axes. In the Monoclinic system, one of them coincides with the axis of crystallographic symmetry (*b*) and the other two lie in the plane of symmetry containing the axes *a* and *c*. In the Triclinic system there is no necessary connection between the crystallographic axis and the directions of maximum,

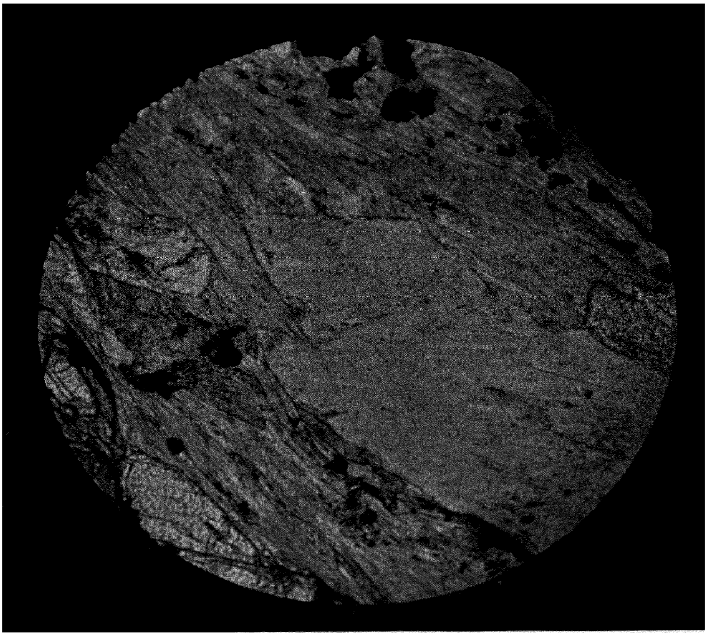


PHOTO-MICROGRAPH 21.
Showing the bi-refringence of magneste. This effect is noticed in minerals which, although colless, have high double refraction, e.g. magnesite, calcite. No. 22.

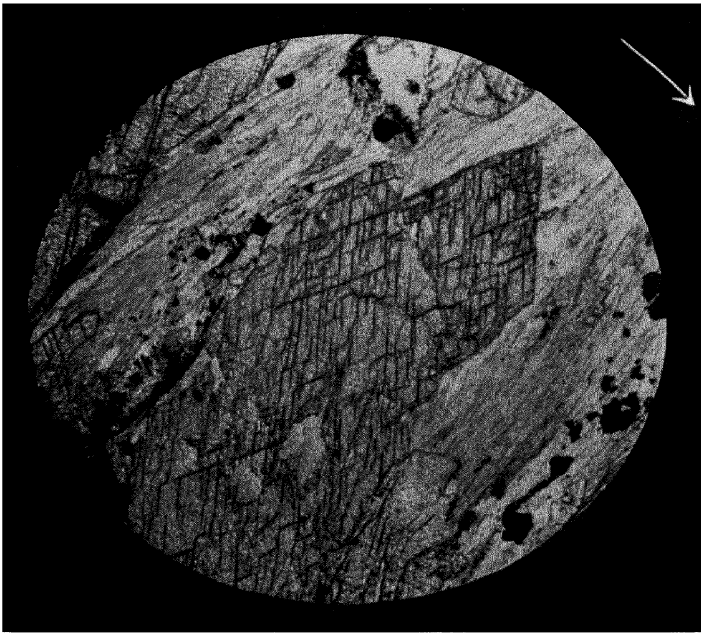


PHOTO-MICROGRAPH 22.
Section 21, rotated 90.

[To face page 83

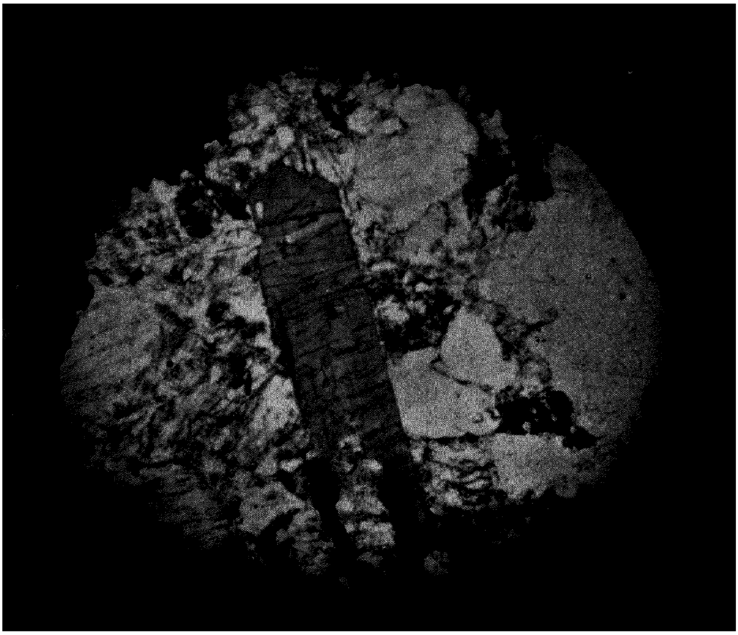


PHOTO-MICROGRAPH 23.
Pleochroism (Tourmaline). Showing the Pleochroism of Tourmaline. Several coloured minerals show this effect, *e.g.* tourmaline, biotite, hornblende, humite, etc. The colours vary with the mineral.

Humite, pale yellow to rich red gold.
Hornblende, pale green to dark green.
Tourmaline, pale brown to dark brown.
Biotite, pale brown to dark brown, almost black.

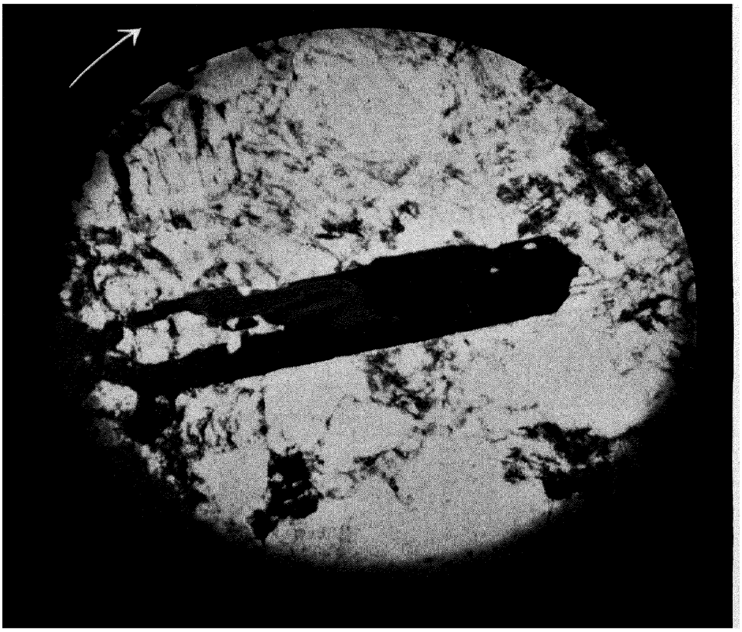


PHOTO-MICROGRAPH 24.
Section 23, rotated 90.

[*To face page* 89.

minimum, and intermediate refractive indices. It is usual to letter the crystallographic axes of biaxial crystals as (*a*) front to back; (*b*) left to right, and (*c*) vertical; and to letter the directions of greatest, intermediate, and least refractive indices (light velocity) as $\mathfrak{a}$, $\mathfrak{b}$, and $\mathfrak{c}$, respectively; and to designate the greatest, intermediate and least refractive indices in the same directions by the letters α, β, and γ, respectively. The two optic axes of biaxial crystals, as already stated, lie in the plane containing the directional or other axes $\mathfrak{a}$ and $\mathfrak{c}$ (i.e. along the axes α and γ) which is the optic axial plane. The optic axes intersect, as a rule, obliquely; and that line which bisects the acute angle of the optic axes is called the *acute bisectrix*, and that bisecting the obtuse angle is called the *obtuse bisectrix*.

It is beyond the scope of this book to elaborate further the optical characters of the crystals of the various systems. Full particulars will be found in Dana's Text Book previously mentioned. A few remarks, however, appear to be necessary to explain the method of working with the accompanying table (compiled chiefly from "Essentials for the Microscopic Determination of Rock-Forming Minerals and Rocks," by A. Johannsen, 1922). It will be noticed that the classification is first into I, OPAQUE; II, ISOTROPIC, and III, ANISOTROPIC MINERALS. Next the ISOTROPIC MINERALS are divided into A, Colourless, and B, Coloured varieties. Further, the ANISOTROPIC MINERALS are also divided into A, Colourless, B, Coloured, Non-Pleochroic, and C, Coloured, Pleochroic types, and each of these, again, is subdivided into (1) Uniaxial and (2) Biaxial crystals. The importance of pleochroism, refractive index, and double refraction is obvious; and it is for this reason that the following explanations have been included.

Pleochroism.—This property is exhibited by many coloured anisotropic crystals, and is due to selective absorption, whereby different colours are visible when the section is examined in different directions in transmitted, plane polarized light (see Photomicrographs 23 and 24). In Uniaxial crystals there are two—of greatest and least—refractive indices; consequently, coloured crystals belonging to the tetragonal and hexagonal systems can only show two different colours, and are therefore said to show dichroism when examined by transmitted, plane polarized light. Biaxial coloured crystals have three different refractive indices—maximum, minimum, and intermediate—and are therefore capable of showing different degrees of absorption in different directions; they may thus exhibit dichroism, trichroism, and, more usually, pleochroism when examined in transmitted plane, polarized light.

Relief (Refringence).—The boldness with which the outline

of a crystal grain is seen in the field of a microscope slide depends on the difference in the refractive index (N) of the mineral and the matrix in which it is embedded. The greater the difference, the higher, or bolder, will be the relief, or boldness, of outline of the mineral (see Photomicrographs 25). As Canada balsam is generally used as the cementing material for mounting mineral and rock sections, it is customary to speak of the relief of a mineral in relation to Canada balsam. The refractive index of Canada balsam is roughly 1,534. The following scale of Relief or Refringence is commonly used :

Order.	Relief.	Examples.
(1)	*Negative* when N is less than 1.54 (Canada Balsam.)	*Fluorite.*
(2)	*Low* when N is greater than 1.54, but less than 1.59 (Muscovite).	*Quartz.*
(3)	*Moderate* when N is greater than 1.59, but less than 1.66 (Enstatite).	*Green Hornblende.*
(4)	*High* when N is greater than 1.66, but less than 1.75 (Staurolite).	*Augite.*
(5)	*Very High* when N is greater than 1.75	*Zircon.*

It is best to make these examinations for refractive indices in ordinary convergent light. On focussing the junction between the mineral and the matrix, a distinct band of light is noticeable—this light band (or Becke line) moves towards the substance with the higher refractive index upon raising the tube of the microscope (see Photomicrograph 25). The method of determination of the refractive index of a mineral by means of the microscope was discussed in the section dealing with the determination of minerals.

Birefringence.—By this term is meant the strength of the double refraction. It is dependent on the difference of the refractive index in different directions, and is therefore only observable in Uniaxial and Biaxial crystals. When there is a great difference in the refractive indices in different directions in a crystal, the birefringence is very marked. This will be understood by reference to Microphotographs Nos. 21 and 22. The following table will assist in making this clear :

Birefringence.		*Mineral.*
Very Weak	1	Leucite
	4	Apatite
	7	Orthoclase
	9	Quartz
	10	Gypsum

Birefringence.		*Mineral.*
Noticeable	12	Kyanite
	13	Hypersthene
	20	Hornblende, green
	22	Augite
Marked	23	Tourmaline
	29	Diopside
	36	Olivine
	40	Talc
Very Strong	60	Biotite
	172	Calcite
	189	Dolomite
	287	Rutile

TEXTURE.—It is not necessary to repeat the remarks which have already been made with regard to the differences observed in the shapes of crystal grains, their interlocked or porous mode of aggregation, and the general textures seen in crystalline and detrital rocks. Such terms as idiomorphic (crystal outlines), allotriomorphic (irregular crystal grains), holo-crystalline, granitic, granular, orphitic, porphyritic, etc., were discussed previously, and the description has been supplemented by the various photomicrographs which illustrate this book. With the help of these and the following determinative table, it should be possible for an engineer to carry out a microscopic examination of most building stones without the assistance of any other book.

DETERMINATIVE TABLE FOR MICROSCOPE SECTIONS.

(1) *Opaque Minerals*, examined by incident (reflected) light.

Iron pyrite is	brass yellow.
Pyrrhotite	bronze yellow.
Chromite	brown.
Hematite	red.
Graphite	black.
Ilmenite	black.
Magnetite	black.

(2) *Isotropic Minerals*, examined by transmitted plane polarised light.

A. *Colourless Varieties.*

	Refractive Index.
Fluorite (fluorspar), occurs as crystals ..	1.433
Opal, occurs as a matrix	1.443
Glass, occurs in cavities and as a matrix ..	1.490
Leucite, generally in polygonal sections ..	1.508
Canada Balsam	1.534
Spinel, in four-sided sections	1.716
Grossularite (Garnet), in rounded grains and polygonal sections	1.750
Spessartite, in rounded grains and polygonal sections	1.811

B. *Coloured Varieties.*	Refractive Index.
Fluorite, as crystals and as matrix	1.433
Sodalite, usually as greenish crystals ..	1.483
Glass, as yellow, green, or dark red inclusions or as a dark matrix	1.490
Canada Balsam	1.543
Spinel, in greenish or red quadratic sections	1.718
Garnet, in rounded or polygonal sections, pink (almandine) and salmon (pyrope) coloured	1.810

(3) *Anisotropic Minerals*, examined by transmitted plane polarised light.

A. Colourless. 1. *Uniaxial.*

	Refractive Index	Double Refraction	Optical sign
Tridymite	1.480	0.001	+
Leucite	1.520	0.0005	+
Quartz	1.55	0.009	+
Calcite	1.50 to 1.65	0.160	—
Dolomite	1.52 to 1.68	0.200	—
Nephaline	1.54	0.005	—
Melilite	1.63	0.005	—
Apatite	1.64	0.004	—
Corundum	1.75	0.009	—
Zircon	1.95	0.054	+

2. *Biaxial.*

	Refractive Index	Double Refraction	Optical sign
Heulandite	1.50	0.007	+
Orthoclase	1.52	0.006	—
Microcline	1.52	0.006	—
Gypsum	1.53	0.01	+
Chalcedony	1.537	0.011	+
Albite	1.537	0.01	+
Labradorite..	1.55	0.008	+
Kaolin	1.56	0.006	—
Anorthite	1.57	0.013	—
Talc	1.55 to 1.59	0.05	—
Topaz	1.60	0.009	+
Aragonite	1.537 to 1.68	0.160	—
Anhydrite	1.57 to 1.61	0.043	+
Muscovite	1.56 to 1.60	0.038	—
Tremolite	1.62	0.026	—
Andalusite	1.635	0.01	—
Sillimanite	1.67	0.022	+
Olivine	1.67	0.035	+
Cyanite (Disthene)..	1.72	0.120	—

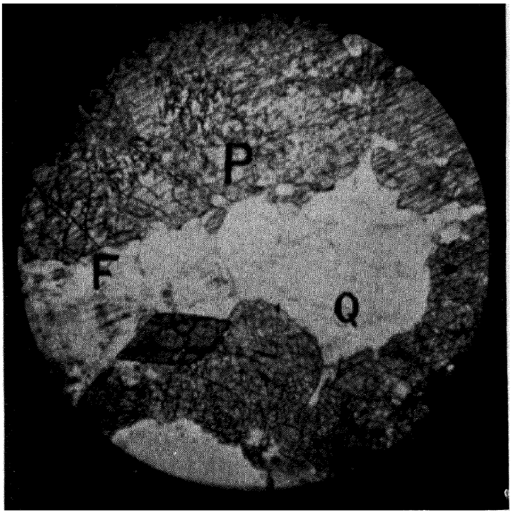


PHOTO-MICROGRAPH 25.

Relative "relief" of some minerals. Showing the differences in the refractive indices of sphene (the lozenge shaped mineral, which has a bold relief or outline), pyroxene (P), weaker than sphene in relief but stronger than felspar. Felspar (F), which has almost the same relief, rather weak, as quartz, and quartz (Q).

B. Coloured, non-pleochroic. 1. *Uniaxial.*

	Refractive Index	Double Refraction	Optical sign
Zircon, pale reddish brown, pink, and green	1.95	0.050	+
Cassiterite, pale red to brown ..	2.00	0.095	+
Rutile, reddish yellow	2.60	0.250	+

2. *Biaxial.*

	Refractive Index	Double Refraction	Optical sign
Phlogopite, pale brown to green..	1.58	0.044	—
Actinolite, pale green	1.62	0.027	—
Olivine, pale olive green ..	1.67	0.035	+
Diopside, pale green	1.68	0.028	+
Augite, pale brown with occasional purple tinge	1.71	0.025	+
Monazite, yellowish green, greenish yellow brown	1.80	0.045	+
Titanite (Sphene), pale yellow orange brown	1.95	0.160	+

C. Coloured, Pleochroic. 1. *Uniaxial.*

	Refractive Index	Double Refraction	Optical sign
Biotite (basal section), pale yellow to chestnut brown and black ..	1.58	0.04	—
Tourmaline, pale brown or green to dark brown or black.. ..	1.67	0.033	—
Rutile, reddish yellow	2.60	0.25	—
Hematite, dark red to black ..	2.70	0.25	+

2. *Biaxial.*

	Refractive Index	Double Refraction	Optical sign
Biotite, pale yellow to chestnut brown and black	1.58	0.04	—
Hornblende (common), green ..	1.65	0.016	—
Hornblende (basaltic), brown ..	1.69	0.022	—
Hypersthene, green to reddish yellow	1.70	0.013	—
Augite, pale brown	1.72	0.025	+
Staurolite, light to dark yellow ..	1.74	0.01	+
Titanite (Sphene), yellow brown	1.95	0.160	+

PREPARATION OF ROCK SECTIONS.—The preparation of thin sections (slices) of rocks and minerals for examination under the microscope, although simple to those who are familiar with this kind of work, presents some difficulties to those not so experienced. The following remarks may therefore prove useful, particularly to those

investigators who are in camp or away from the conveniences of a laboratory. The methods described are those performed by the Indian section cutters attached to field parties of the Geological Survey of India. It will be seen that the processes are not unlike those described by Frank Rutley in his valuable little book, "The Study of Rocks," 1904, pp. 59–74.

The first operation is to obtain a flat chip or flake from the specimen of which a section is required. This is readily accomplished after a little practice with a small knapping hammer; needless to say, much depends on the hardness and friability of the material. Limestone, coal, bauxite, and other such comparatively soft substances, are easily ground and require much less expenditure of energy, but greater care, than hard rocks such as quartzite or tough minerals such as fibrolite.

Experience soon shows that very small chips are not only difficult to hold and mount, but tend to grind too rapidly at the edges during the earlier manipulations, while too large a fragment involves an unnecessary amount of grinding. For building stones and the rocks commonly met with, the most satisfactory kind of chip varies from about 1 to $\frac{3}{8}$ inches square to $\frac{1}{4}$ or $\frac{1}{8}$ inches thick. In the case of coal, bauxite, and other soft specimens, larger pieces are recommended.

When a chip of suitable size and shape has been secured, the next operation is that of grinding it—using a circular motion of the hand—on a cast iron plate (about 13 inches by 9 inches by $\frac{3}{8}$ inches) with emery and water, until a smooth surface has been prepared. This surface, after washing off the emery powder, is further ground with finer emery powder and water, and after the surface thus obtained is washed clean, the surface is polished with the finest emery flour and water on a smooth brass plate (about $6'' \times 6'' \times \frac{5}{16}''$). An occasional drop of kerosene oil is often added, towards the final stage of polishing, to reduce friction. In some rare cases the polishing is completed with dry rouge on a tightly stretched piece of parchment. It is necessary to add here that coal, bauxite, and other such very soft substances, should not be ground or polished with an abrasive, as the grains of emery become embedded in the mineral, and cannot afterwards be removed. Such sections are seldom cut in camp, but should it be necessary, chips can be cut off with a tenon saw, the preliminary grinding done with a fine file, and the polishing with a hone stone. In each case the circular motion is important, as with the friable coal the chip may break up, while with the bauxite distortion may take place. Before beginning the grinding of coal, bauxite, or other such porous soft substances, it is a good plan to "cook" them for some time in a dish containing Canada balsam mixed with benzol or methylated spirit—care being taken that the temperature of the liquid does not

exceed 100° C., otherwise volatile constituents or the contained water may be driven off and the structure of the substance destroyed. However, as a rule, it is better to leave such mineral substances until sufficient experience in the preparation of sections of the commoner types of rock has been acquired.

Elaborate slicing and polishing machines are now available, and there are many lapidaries who undertake this kind of work nowadays; but it is far better if one is likely to be in camp for long periods at a time to grind and mount rock sections without such aids.

To continue the hand operations—the chip, particularly the polished surface, is washed free of any emery particles. The next operation is that of fixing the polished surface to a plate of glass. If the chip is small and flat, it may be directly mounted on the glass slide which is, roughly, $1'' \times 3'' \times \frac{1}{64}''$, and made of good plate glass free of strain. With stouter chips or larger fragments, the normal procedure is to mount it on a glass slab $1\frac{1}{2}$ inches square and $\frac{3}{8}$ inches thick, having rounded edges and corners.

The glass slab (or slide) is placed on an iron or copper sheet supported by a tripod stand over a spirit lamp, *and warmed*. A few pieces of dry Canada balsam are placed on the surface of the glass slab.* The rock chip, with its polished surface uppermost, is also placed on the metal plate, but not on the glass slab. When the Canada balsam on the glass slab becomes fluid (it should never be allowed to overheat so as to boil), the warmed chip should be placed on the Canada balsam, with the polished surface towards the glass slab, and pressed on to the glass slab with a firm gradual twist until the two surfaces are in contact. There is, of course, a thin film of Canada balsam between—it is the cementing medium.

If the glass slide is used at this stage, a piece of thin asbestos cloth should be placed under it on the hot metal plates, and no Canada balsam is put on the surface of the slide till it is hot. In this case the rock chip is "cooked" in an evaporating dish, containing Canada balsam, on the hot metal plate. The Canada balsam in this dish should not be overheated—a temperature of from 150° C. to 180° C. being sufficiently high for most purposes. Just before removing the chip from the dish of hot Canada balsam, a little of this fluid is placed on the warm glass slide. Next, the chip, with its polished side downward, is gently but firmly squeezed down on the glass slide and the superfluous Canada balsam scraped off into the evaporating dish. The slide, when the balsam has become fairly dry and non-adherent,

* Messrs. Voigt and Hochgesang of Gottingen (Germany) have a substitute for Canada balsam. It is named kollolith and is available in fluid or solid form. It is soluble in Xylol and has a refractive index of 1.5354 (sodium flame at 18°C). The price is 1/6 a tube.

should be carefully examined from below to see if any air bubbles have been trapped between the polished surface of the chip and the glass slide. This is also done in the case of the glass slab, but it is of greater importance that air bubbles should be excluded from the slide mounting.

If these manipulations have been rapidly performed and care used in sliding the polished surface of the chip over the balsam on the slide, air bubbles will be avoided. Should an appreciable number of air bubbles be seen, the slide (or slab) must be re-heated, the chip detached, and both surfaces—that of the glass slide and the polished face of the chip—must be cleansed of Canada balsam by washing with turpentine or benzol (spirits of wine—methylated spirits is now largely used), and the whole operation of fixing repeated.

When the mounted chip is successfully attached and the Canada balsam is hard, the upper surface of the chip can be ground down. This operation is a little more difficult in the case of the mounted slide than if the chip were fixed to a glass slab. The grinding with fine emery and water on the cast iron plate is continued until the chip has become a thin wafer. The pressure of grinding is slightly reduced, and when the thin section is translucent, the emery is all washed off. The final polishing is done with the finest emery flour and water on the smooth brass plate. A few drops of kerosene oil are sometimes added towards the end of this operation to reduce the abrasion. Occasionally the polishing is completed with rouge on a stretched piece of chamois leather.

At this stage the mounted, but yet uncovered rock section, is available for any preliminary examination that may be necessary. It is useful to put a drop of turpentine on the matte surface of the section, or at least to moisten it with water, before placing the slide under the microscope. This wetting considerably improves the transparency. Chemical tests, such as the action of acids (for etching) and dyes (for staining) can also be carried out at this stage. Most of the physical determinations, except seeing that the section is not too thick, are performed when the rock section is finally covered.

If the stage has been ground and polished on a thick glass slab, the next operation is that of transferring it to a glass slide. The glass slab, with the section uppermost, is placed on the hot plate and warmed until the cementing balsam is quite fluid. Meanwhile a shallow dish, or a watch glass, or small evaporating dish containing turpentine or methylated spirits, is placed ready to hand. When the glass slab is hot, the section is slid off into the methylated spirits in the evaporating dish. This is performed by first pushing aside the spirit lamp, placing the dish on a thin piece of asbestos on the hot plate, and, after tilting

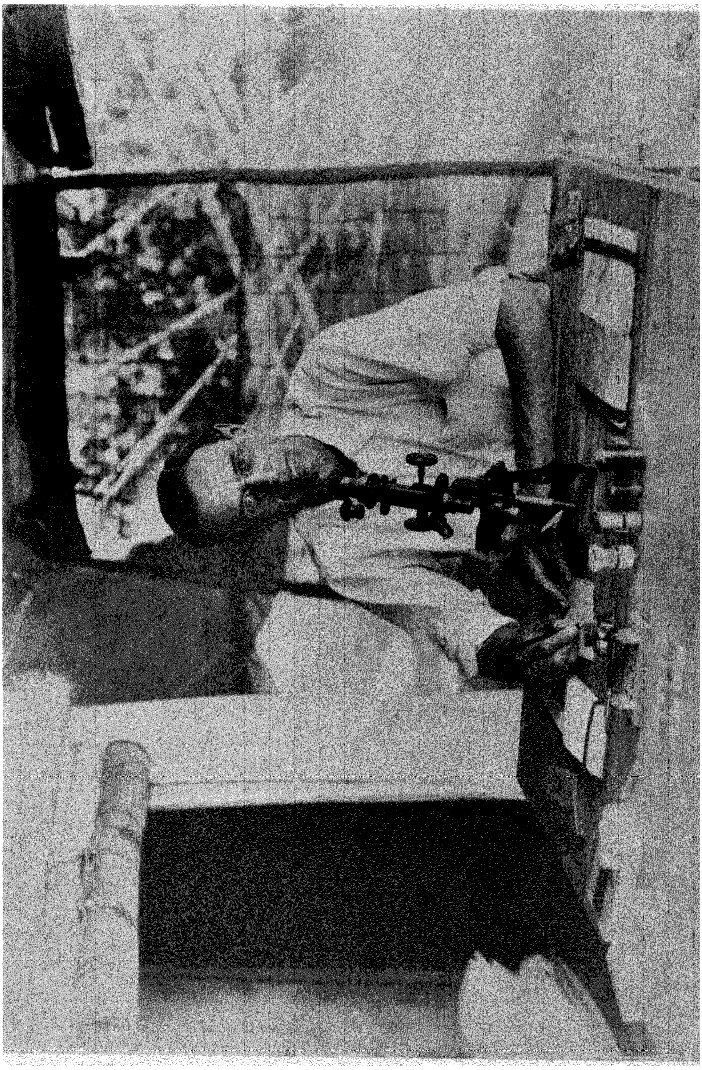


Photo by C. S. Fox.] A WELL-KNOWN PETROLOGIST AT WORK. [*D.G.S.I.*

Dr. L. Leigh Fermor, F.R.S., is seen with his microscope under field conditions. On the table arranged for scrutiny are the microscope slides of rock sections, together with his notebook, geological map, accessories and the specimen under examination.

[*To face page* 96.

Photo by C. S. Fox.] [*D.G.S.I.*

EQUIPMENT FOR MAKING ROCK SECTIONS.

The Section-Cutter is shown with his full field equipment. In front of him are the grinding and polishing metal plates. On his right the tools, lamp, Canada balsam, and the box to hold these materials.

[*To face page* 97.

the glass slab with a pair of cork-tipped tongs, pushing the thin section along with a blunt wire. The methylated spirits in the dish is next brought to the boil either by bringing the spirit lamp under the hot plate or by holding the dish in a pair of crucible tongs over the flame. In each case ignition of the methylated spirits is to be avoided, and the heating is not to be prolonged after the methylated spirits has been slowly brought to the boil.

The dish is next carefully supported, and the section turned over and over very gently with a camel hair brush, and thus washed with methylated spirits. A glass slide ($1'' \times 3'' \times \frac{1}{16}''$), with a drop of Canada balsam on it, is meanwhile placed on the asbestos sheet on the hot plate and slowly heated. The section is next removed from the dish by causing it to adhere to the side of the wire needle and the excess of methylated spirits removed from the section by touching its lower edge with the finger on to which the methylated spirits will flow.

If the Canada balsam on the glass slide has not meanwhile been spoilt by boiling, the lower edge of the section is then placed on the Canada balsam and allowed to subside slowly on and into the balsam. It is assisted with the needle, and the greatest care must be taken to avoid bubbles. When the section has been completely immersed in Canada balsam on the slide, a thin clean cover glass about $\frac{7}{8}$ inches diameter, and held in a pair of forceps, is slowly heated, and then let down gently on the section. Again care is necessary to avoid the occurrence of bubbles, and the cover glass is finally pressed down gradually to bring it close to the section and drive out bubbles. This is most satisfactorily accomplished with a slight rotary motion. The superfluous balsam is then scraped and wiped off with benzol to remove the remainder on the surface of the slide and cover glass. The mounted slide is then labelled and is ready for examination.

On returning from camp, and before putting the mounted sections away for future reference, it is advisable to mark the slide by scratching on it the number with a diamond pencil; this is particularly necessary in India, where the labels occasionally fall off in dry weather.

The section cutters field equipment is contained in a box ($20'' \times 12'' \times 15''$) which, when fully packed, weighs about 14 lbs. The contents of the box are as follows:

List of Articles Necessary for the Section-Cutting Box.

Iron plate	$13'' \times 9'' \times \frac{3}{8}''$
Brass plate	$6'' \times 6'' \times \frac{5}{16}''$
Copper plate (round) for lamp	$5''$
Tongs	1
Pair of scissors	1
Section holder	1

Label brush	1
Needle	1
Forceps	1
Clip	1
Microscope slides	300 (measuring $3'' \times 1''$ each)
Thick glass	50 (measuring $1\frac{1}{2}'' \times 1\frac{1}{2}'' \times \frac{3}{8}''$)
Cover glass	2 oz. ($\frac{7}{8}''$)
Glass rod	1 ($8''$)
Canada balsam	2 lbs.
Small hammer	1
Slide cleaning dish	1
Tripod	1 ($7\frac{1}{4}'' \times 5'' \times \frac{3}{4}''$)
Spirit lamp	1 ($6\frac{1}{4}'' \times 3\frac{1}{2}''$)
Spirit can	1 ($8'' \times 6\frac{3}{4}''$) to contain 7 bott. spirit

Carborundum tin No. 100 (measuring $6\frac{3}{4}'' \times 3\frac{1}{2}'' \times 3''$) to contain 4 lbs.
Carborundum tin No. 50 (measuring $6\frac{3}{4}'' \times 3\frac{1}{2}'' \times 3''$) to contain 4 lbs.
Carborundum powder No. 15M (measuring $6\frac{3}{4}'' \times 3'' \times 1, \frac{15}{16}''$) to contain $1\frac{1}{2}$ lbs.

Lamp screen, tin	1

CHAPTER VI

CHOICE OF MATERIALS

GENERAL REMARKS.—Actual tests for ascertaining the crushing strength, resistance to abrasion, toughness under impact, weathering qualities, etc., are naturally the most satisfactory means of ascertaining the properties of a rock. The engineer may not, however, be able to carry out these tests owing to the costliness of some of the apparatus required. In such cases a petrological examination can not only be carried out quickly, but will prove reliable. The best procedure is that of preparing thin sections of the rock and examining the slides under the microscope. Three or four such sections can be cut and mounted as slides in a day by a trained section cutter, so that in this way several samples can be collected in various parts of a quarry, sectioned and examined, and a very fair idea obtained of the material in the quarry. With a little practice it is possible to tell at a glance if any of the mineral components of a fresh-looking rock are decomposed. The altered condition of a single constituent, *e.g.* felspar of a medium-grained granite, may very seriously affect the strength and durability of the rock as a whole. Concrete in which the aggregate is granite with decomposed felspar which has been used dry will be subject to serious contraction. It is thought that the decomposition of the felspar continues, and that the kaolin, hydrous silicate of alumina, which is formed extracts the necessary moisture from the matrix of the concrete, thereby producing shrinkage in the mass. A dam made of concrete with such ingredients is certain to contain cracks which might result in serious loss by leakage, or possibly in the collapse of the dam. Much, obviously, depends on the knowledge of the investigator. He should be able to identify the common minerals and rocks in hand specimens, and be familiar with the weathered appearance of the more important types of rock and their field relationships. If, in addition to this, he has trained himself to cut and prepare and examine either thin sections or polished surfaces of rock under the microscope, he will be equipped for very detailed work. The apparatus required for cutting and making microscope sections or for polishing rock surfaces is simple and inexpensive. The whole outfit can

be packed away in a box 20" × 12" × 15", and it is possible to teach an intelligent Indian servant to cut sections in three or four months.

Numerous books have been published on the subject of microscopic examination of thin sections of rock and the determination of translucent and opaque minerals in transmitted and reflected light. The first glance at a section of rock through a microscope reveals the size and shape of the component minerals, the open or interlocked aggregation of the grains, and the general texture of the rock. With a little patience it is possible to ascertain the several constituent minerals and their degree of alteration. All these little facts, when pieced together, provide sufficient data to form an accurate opinion as to the suitability of the rock for various purposes. This aspect of the subject was briefly touched upon when discussing the more important types of rock in the chapter, 3, on The Principal Rock Types.

CLAYS.—There are numerous classes of clay, from the dark blue brick-clays and red loamy varieties to the pale cream fire-clays and white somewhat non-plastic greasy kinds known as kaolin. The colouring matter in clay is usually an oxide of iron. When this substance is present in appreciable quantities, the clay is generally readily fusible, and bricks made of this class of clay are liable to over-burning with the formation of clinker bricks. This burnt brick is sometimes useful as a protective material for banks, etc., liable to the scouring action of streams. The colour of the bluish clays when burnt is generally dark or bright brick-red; if lime is present, the burnt brick is generally yellow or buff in colour. Purer clays stand much higher temperatures and merge into fire-clays, etc. The characteristic property of clay is its plasticity; it is a property which being due to the physical rather than to the chemical condition of the material can only be determined by experiment. Some clays shrink enormously on drying or burning, and require an addition of sand or chaff, etc., to reduce this contraction. The subject of clay for various purposes is a very wide one, the treatment of which is outside the scope of this book. Dr. J. W. Mellor draws attention to the presence of many valuable fire-clays in coal mines in the Stourbridge area. He says some of these mines are now only worked for the excellent clays they contain. (See "Unknown Clays in Coal Mines," *Colliery Guardian*, Vol. CVIII, 1915, p. 567; see also "Microscopic Examination of Clays," *Journal Washington Academy of Science* (Vol. IX, pp. 113–116, 1919), R. E. Somers, extract in *The Quarry*, Vol. XXIV, July, 1919, p. 185.)

In many parts of the world the soil is impregnated with mineral matter (salts), which appears on the surface of the ground in dry weather as an efflorescence. If bricks are made of the clay of these areas, the salt, if not removed, will often remain unchanged in burnt

bricks; consequently, when the bricks are used for building purposes, an encrustation of salt may in time appear on the exposed surfaces of the brickwork, particularly on the shady or damp side of walls. The salts which most frequently cause these discolourations are the sulphates, chlorides, and carbonates of potassium, sodium, aluminium, magnesium, and, especially, calcium. An efficient method of detecting the presence of soluble salts in a brick is that known as Dr. Meckler's test. In this, the brick (only unglazed bricks can be examined by this means) is placed over a fairly wide-mouthed bottle containing distilled water. Keeping the brick carefully pressed on the bottle, the two are quickly turned over without allowing the water to spill, and the brick with the inverted bottle uppermost is supported on two glass rods over a dish. The brick will slowly absorb the water, which in turn will percolate through the brick to the lower surface, carrying any soluble matter with it. This water will be finally evaporated and leave behind an encrustation of salt, if there is any, on the under surface of the brick.

SANDS.—The size of the grains determines whether a loose, gritty substance should be called a gravel, a sand, or silt. When the particles are all less than 0.01 mm. in diameter, the substance is mud or clay. In fine silt the particles vary in size from 0.01 mm. diameter to less than 0.05 mm. diameter; coarse silt from 0.05 mm. to 0.1 diameter. Fine sand is composed of grains from 0.1 to 0.25 mm. diameter; medium sand, 0.25 to 0.5 mm. diameter; coarse sand from 0.5 to 1 mm. diameter; and very coarse sand between 1 and 2 mm. diameter. The particles of gravel exceed 2 mm. diameter (see "British Glass Sands," by Professor P. G. H. Boswell). The opinion of a qualified metallurgist and mining engineer is that the following particle-sizes are those to which definite names are ascribed:

Particles passing through a square aperture of a width	*Name.*
Varying between 2.5 and 0.75 m.m.	Coarse Sand
,, ,, 0.75 ,, 0.10 ,,	Sand
,, ,, 0.10 ,, 0.05 ,,	Fine Sand

(Communicated by H. L. Sulman to Messrs. Hatch and Rastall.) See also "The Geology of Sands and Aggregates for Concrete-Making," by P. G. H. Boswell in *The Quarry*, Vol. XXIV, September, 1919, p. 242.

Although there are many kinds of sands composed of widely different substances, *i.e.* magnetite, garnet, zircon, monazite, etc., the term sand alone usually implies the presence of quartz grains only. In a number of cases sands are largely composed of equal-sized (graded) particles, either large or small. Sands composed of grains of assorted sizes are most common, and frequently require screening to obtain

equal-sized grains for particular purposes, *i.e.* moulding sand. When used for making mortar, the angularity of the grains is an important factor. Quartz sand will usually be found in streams which drain large areas in which granite or sandstone rocks are exposed. River sand is, as a rule, more angular, *i.e.* sharper, than sea sand, because it is usually nearer its source of origin, and is consequently less worn and rounded; but this is not a reliable guide, as river sands may be derived from sandstones which may represent the deposited sands of pre-existing rivers. The most efficient method of determination is that of taking samples of the sand and examining the grains with a lens or under the microscope. The precaution of washing sands which contain soluble salt is not always taken, with the result that the mortar which is subsequently made may give rise to dampness and discolouration of interior walls.

PEBBLES.—Pebbles may consist of a variety of hard rocks of igneous, sedimentary, or metamorphic origin. The hardest and best-known pebbles are of quartzite. These pebbles, because of their great hardness, are very suitable for the aggregate of concrete. The whole object in the preparation of concrete is to reconstruct in the artificial stone a texture and mineral composition similar to those rocks which have the greatest strength, durability, and toughness. The rounded, smooth surfaces of pebbles do not allow the cementing matrix to hold firmly, and it is therefore advisable to use broken pebbles, because the angular fragments bind much more strongly (see Photograph VIII).

Well-washed fragments of many fine to medium-textured rocks such as basalt, andesite, and trachyte, are also very suitable for concrete-making.

In the chapter on Rocks (sedimentary rocks), reference was made to the shapes of pebbles of certain origin. River pebbles were said to be of an elongated shape (prolate spheroids), because they rolled steadily down-stream, while sea-shore varieties were said to occur sometimes as flat pebbles (oblate spheroids), because they were subjected to a sliding movement up and down the beach. The flatness may be due to the lamination of the original material, and the elongation to the jointing of the rock from which the fragment has been derived. In the majority of cases, the pebbles are rounded and irregular in shape.

Some idea of the durability of quartzite pebbles may be obtained by taking the case of the shingle of the Chesil Bank in Dorset. Many of the quartzite pebbles in this bank have come from the conglomerate bed exposed in the cliff of Budleigh Salterton in Devon. The accepted history of the Chesil Bank pebbles is as follows:

To-day they are being worked along the beach between Abbotsbury and Portland by the sea waves; they were, however, derived, as pebbles, from some old plateau gravels, fragments of which are still to be seen on the land in that vicinity. The Tertiary gravels had previously represented material which came directly, also as pebbles, from the Bunter Pebble Beds, which trend inland northward from the coast at Budleigh Salterton. At a still more distant epoch of geological time, the Triassic Period, the Bunter Pebble Beds were formed from quartzites of Ordovician Age. Thus it is seen that the pebbles represent material of Lower Palæozoic Age, rounded into pebbles in early Mesozoic times, and subsequently water-worn in the Tertiary Period, and still exist as pebbles to-day.

ROAD METAL.—It is well known that materials for road metal should have good wearing qualities, and consequently, be both hard and tough (see table of "Selected Examples of American Tests on Road-Stones," quoted by J. A. Howe in his "Stones and Quarries" (p. 72) from *U.S. Bureau of Public Roads*, *Bull.* 31). The best rocks for road metal are those consisting of equal-sized grains of medium to fine texture, with an interlocked, ophitic arrangement of tough mineral of the requisite hardness—particularly basalt, andesite, trachyte, diorite and similar varieties. Hard, brittle stones like quartzites, or the relatively friable sandstones, are unsuitable, as the fragments are crushed against each other under heavy traffic, with the result that they grind to dust. The hardest argillaceous rocks, such as phyllite and slate, are too soft to withstand the heavy wear of a road surface. Hard limestones, although relatively soft and friable on ordinary watered roads, are being used to a considerable extent in a particular way: the fragments are laid dry and tarred, and after preliminary rolling a protective carpet of asphalt and sand is put on as the wearing surface. The advantages of using material which has been hand-broken in preference to that which has been obtained from a jaw-crusher have frequently been discussed. The blunt-pointed hammer breaks the stone by impact along definite directions without damage to the body of the stone, whereas the machine crushes the whole stone, loosens its texture, and makes it less tough and more friable.

There are several considerations which affect the choice of road metal. If water is to be used in the construction of a road, perhaps well-washed fragments of the basic types of the igneous rocks are the most suitable; this material wears exceedingly well, and the decomposition products of the mineral components result in the formation of secondary minerals between the fragments, which cement adjacent pieces and prevent them rubbing against each other, thereby assisting

in the consolidation of the road. When tar is to be used, the road metal should be used in a perfectly dry condition, as the tar holds better to a dry surface than to one which is wet. Experimental work has shown that limestone and tar adhere to each other particularly well, whereas tar and quartzite do not; the igneous rocks occupy an intermediate position with regard to this peculiar property of adhering to tar (see "Tarred Granite Macadam," by W. Jenkinson, *The Quarry*, Vol. XXIV, January, 1919, p. 21).

Limestone, however good, is not hard enough to resist abrasion when exposed to steel-studded tyres and iron shoes of horses; consequently such road surfaces require protection. The method of saving such roads is to cover the surface of the road metal with a thin layer of asphalt in which coarse sand has been mixed, and also to sprinkle sand on the asphalt "carpet" while it is still hot; by doing this, the actual wear is taken by the grains of hard quartzite. This type of protective carpet is also being used for other kinds of road surfaces.

One of the most serious difficulties appears to be the grinding action which takes place between adjacent fragments of the road metal when the road is used by heavy vans, etc. Tar, by sinking into the crevices of the road metal, appears to be an excellent remedy for this kind of road deterioration, as it acts as an elastic cushion between the fragments.

Another evil is that of the development of ridges from 16 to 24 inches apart, across the length of a road. All classes of roads, except those paved with stone setts, appear to become corrugated when used by heavy, fast-moving vehicles. Various explanations and remedies have been suggested. To a geologist this phenomenon has all the aspects of an expansion, longitudinally, of the whole volume of the road-metal bed, combined with "creep" due to the tangential pull and push effect exerted on the road surface by the wheels of fast-travelling, heavy vehicles. The thicker and more uniform the nature of the road metal, the further apart will be the corrugations, while thin surface dressings will wrinkle more closely. It resembles, in miniature, certain phenomena seen on a vast scale in some parts of the world: for example, the earth movements in Asia have wrinkled up the bedded strata of a marine region into the highest mountains of the world, whereas the ancient stable land area of India has remained practically immune from similar displacements. In some ways ordinary macadam roads are analogous to rigid steel rails in that changes of temperature cause buckling, while high-speed wheeled traffic produces "creep." It would appear reasonable, by continuing the analogy to present practice, to use slightly separated, short lengths

of sufficient weight, so that the passing traffic cannot impart an appreciable velocity to the mass. On this assumption, the most satisfactory way of protecting a macadam road would appear to be to cut it into sections by introducing deep ribs diagonal to the road. These ribs would localise the expansion and laterally deflect the tendency of the surface to "creep." The use of well-laid, heavy blocks of stone or concrete, arranged diagonally across the road, should also render a road immune from corrugations. If the blocks were 24 inches across, they would span the maximum corrugations which at present occur, the spaces between the blocks would allow of enough "play" for expansion, and the weight of the blocks would offer a heavy damping effect to the forces which cause displacement.

BALLAST.—It is not unusual for railroad engineers to ask a geologist's opinion with regard to the suitability of a given stone for "ballast." They state that experience has shown that some varieties of angular stone crush to powder, and thus cause the line to sag. They also find that rounded materials, such as pebbles and shingle, get squeezed out by the pressure of heavy engines, and, consequently, result in the sinking of the line. From these facts it is clear that for specially heavy lines quartz rock and certain quartzites (those with a siliceous matrix) should not be used, and pebbles of this material are also to be avoided. For most other purposes almost any fresh igneous rock will answer very well; among the sedimentary rocks, argillaceous or ferruginous sandstones and hard limestones will generally prove satisfactory; while most metamorphic rocks of the gneissose type will be reliable—marbles and granulites should answer very well, but fissile rocks, such as slippery schists and slates, should be avoided.

An excellent work on "Attrition Tests of Road-Making Stones," by E. J. Lovegrove, "with Petrological Descriptions" by J. S. Flett and J. A. Howe, was published by the St. Brides Press, Ltd., in 1906. The rocks examined and described consisted of those belonging to the granite group, porphyry and porphyritic group, basalt and diabase group, andesites, hornfels, quartzites and sandstones, limestones and dolomites, and flint. The general conclusions are interesting, and the *condition*, fresh or altered, of the rock is discussed as followed:

"There is much confusion among practical men unacquainted with petrology arising from an improper conception of the meaning of the terms 'fresh,' 'altered,' 'decomposed,' as they are applied to rocks or the minerals composing them. If we use the terms 'fresh,' and 'decomposed'=rotten, we in general convey the ideas of goodness and badness, respectively; this is not the case when reference is made to rocks. When we speak of a mineral being in a fresh condition, we mean that it possesses its inherent properties in an unimpaired

state; if the original or primary minerals are not altered by subsequent processes, they are said to be 'fresh.' A fresh *rock* is one in which the minerals that compose it are fresh. When a mineral within a rock alters or is decomposed as the result of certain forces acting upon it, it breaks up usually into one or more *new minerals*, each one in its own way being as 'fresh' as the original mineral.

"It is possible for the alteration of a rock to make it actually stronger than before. Some of the new minerals produced by alteration (molecular rearrangement) may be an improvement upon the original; others may be the reverse. When a rock is acted upon by surface weathering agents, it frequently happens that certain selected mineral substances are removed, and it is thereby weakened, or softer minerals are introduced.

"For this reason it has been suggested that the term 'decomposition' should be confined to surface weathering, while 'alteration' is maintained for more deep-seated molecular rearrangements within the rock; but the suggestion is not regularly acted upon.

"The microscopic examination of the rock shows what the action of the alteration is, and whether it is likely to be beneficial or not in its effects; thus the alteration of augite to chlorite produces a result that is usually inferior to the original in wearing properties, while the alteration to uralite appears to be superior.

"The very best rocks in these tests are altered rocks, and as a general rule a certain amount of alteration of the felspars seems to be an advantage. The reason for this is that the alteration produces a *number* of mineral units where formerly only *one* existed; in other words, the texture is made finer and often the interlocking of the grains is made more complete. A large fresh crystal of felspar, by its rigidity and perfection of cleavage, is less able to resist impact than the same volume of substance in the condition of an intimate mixture of granules of mica, sericite, kaolin, or epidote, especially if they are united by a quartzose cement, as is frequently the case.

"In short, alteration by reducing the size of the grains and felting them more closely tends to enhance the *toughness* of the stone. It is only when large quantities of soft minerals are introduced, or some ingredient is removed, usually by surface agencies, that alteration is liable to be inimical to the wearing properties."

PAVING SETTS AND FLAGS.—Besides possessing the properties of hardness, toughness and durability, stones used for setts or flags should wear uniformly and retain a rough surface. Coarse textured rocks, or those with large porphyritic crystals with marked differences of hardness between the mineral components, etc., are generally unsuitable for this purpose; the softer parts easily wear into holes under the impact and attrition of steel-studded tyres or the shoes of a heavy horse.

The medium and fine-textured varieties of the igneous rocks make good paving setts, but they tend to become polished with wear, and

the road surface becomes slippery in consequence, particularly in wet weather.

Certain hard felspathic sandstones and quartzites of medium-grained texture make ideal paving stones.

Although the felspar and quartz grains have approximately the same hardness, the easy cleavability of the felspar causes the grains of this mineral to break into angular fragments under impact, whereas the quartz grains are merely rounded. The scale of this wearing action is so small that the inequalities thus produced result in the surface of the stone remaining rough. A rock having a hard, strong matrix somewhat softer than the embedded quartz grains (as in the asphaltic protecting carpet of tar macadam roads) would answer the same purpose.

Some fine-grained marbles, calc-gneisses and some schistose rocks are of suitable texture and mineral composition to retain a rough surface when exposed to wear as paving stones. They are usually less resistant to abrasion than the hard felspathic sandstone flags which are so frequently used for paving purposes; and, as a result, these softer rocks are not serviceable in positions exposed to considerable wear. Many varieties of marble and some calc-gneisses make excellent ornamental flooring slabs, and are used for this purpose.

The extensive use of so-called patent stone is an indication that, with suitably chosen ingredients, an artificial stone pavement can be prepared with excellent wearing properties, and often far more cheaply then could be prepared with natural stone. The uniformity of the artificial material can be guaranteed, and the large floor slabs can be readily made.

BUILDING STONE.—Strength and durability are the two most important considerations in choosing rock for building purposes. Particular characters of the stone may render it more suitable for one class of work than for another. Special features of a building may require stone of definite size and shape; the limitations of many varieties of rock may soon be discovered when it becomes necessary to utilise such materials in engineering work. Stone which is to be submerged, as in dock walls, breakwaters, dams, etc., is liable to be attacked by boring animals, particularly in sea water; limestones are specially liable to injury from such animals. The Plymouth breakwater was bored into by *Cliona celata* and *Saxicava rugosa*. The harbour works at Wairoa, Hawkes Bay, New Zealand, which are built of "papa" rock (hard shale) have also been seriously damaged by similar marine boring animals (see "Marine Boring Animals Injurious to Submerged Structures," by W. T. Calman). Almost any kind of rock can be used for ordinary building purposes if it is available in

quantities. Some varieties are stronger and "dress" better than others. Coarse or fine-textured types, provided they are not unduly soft or friable, may answer equally well, and engineers are familiar with the commoner kinds. Problems arise when heavy structures are to be built or great columns or huge blocks are required, or when long slabs or thin sheets are wanted, and the material has to be specially quarried for this purpose (see "Selection of Stone for Public Buildings," *The Quarry*, Vol. XXV, September, 1920, p. 235; and "The Stones of London," by J. V. Elsden and J. A. Howe, *The Quarry*, Vols. XXVI, 1921, and XXVII, 1922; and "Stones and Quarries," by J. A. Howe.

The last author discusses the various types of stone in the following order: Limestones, Sandstones, Slates, Marble, Granite, other Igneous Rocks. Presumably he takes them in this order as indicating their relative importance.

A few examples of the stone used in certain important buildings, monuments, and for industrial purposes, may not be out of place here:

Portland Stone has been used in the following monuments and buildings in London (see "Portland Stone Quarries," by J. Griffiths in *The Quarry*, Vol. XXVI, 1921, p. 217):

(1) St. Paul's Cathedral.
(2) The Monument marking the limit of the Great Fire of London in 1666.
(3) The London County Council's Hall on the south bank of the Thames facing Westminster.
(4) The Port of London Authority's Building on Tower Hill.
(5) The Victory Arch at Waterloo Station.

As regards the choice of Portland Stone for St. Paul's Cathedral:

"Wren appears to have been influenced in his selection of the stone rather by the size of the blocks than by their quality, although during the construction of the present Cathedral, which took place between 1675 and 1710, he had sole control of the Portland quarries, and took the greatest care in the selection and proper seasoning of the stone before use. In his careful adherence to the principles of classic architecture, Wren was compelled to limit the diameter of his pillars to the size of the stone that could be obtained, and he found the Portland quarries more suitable than any other known at that time to yield the blocks he required." (See "The Stones of London," *The Quarry*, Vol. XXVI, 1921, p. 174.)

FOSSIL LIMESTONES.—The pedestal of General Gordon's statue in Trafalgar Square is made of Carboniferous Crinoid limestone from Derbyshire (The Peak).

The statue of King Charles I, at the top of Whitehall, is built on a base of Purbeck limestone.

Sandstones are widely used for building and other purposes. An excellent paper dealing with "The Newcastle Grindstone Industry," by J. Rickerby, appeared in *The Quarry*, Vol. XXVII, 1922.

The rock used for this purpose is Millstone Grit. It is a freestone of great uniformity in particular beds and is also used for the manufacture of pulpstone (to deal with wood pulp in paper making). A grindstone foot = 7 inches, so that an 8-foot stone is 56 inches diameter.

Other examples of the use of Millstone Grit are given on page 195.

SLATE.—There are numerous papers which discuss the use of slate for building. One of these—"Slate and Its Modern Uses," by Professor O. T. Jones, *The Quarry*, Vol. XXVI, January, 1921—states that:

"although on an average only one-twentieth part of the quarried material is obtained as finished roofing slates, the waste material is now being utilised for a variety of purposes."

Among other papers may be mentioned "A Scientific Method of Quarrying Slate," by Ed. Delcourt, *The Quarry*, Vol. XXVII, 1922, p. 52.

Slate, as has been stated, is a metamorphic rock. It may result from the metamorphism of clays and shales, and occasionally dynamically altered volcanic rock. For example, the Welsh and Cornish slates (dark bluish and purple) are of sedimentary origin, the altered product of clays and shales; whereas the slates of the Lake District were originally volcanic rocks.

TRACHYTE.—This comparatively rare rock is seldom found in sufficient quantities for use as a building stone. The whole of the plinth of Australia House in the Strand is made of trachyte brought from New South Wales.

From the remarks made in previous chapters, or from personal experience of building stones, the engineer should not find it difficult to choose correctly the right kind of rock. He will be familiar with the fact that great blocks are generally only obtainable from coarse-textured igneous rocks or from massive sedimentary types; in these the joint planes are further apart than in the fine-grained varieties. Generally it is not easy to obtain large blocks suitable for columns from laminated beds or from thinly-banded types of rock. In exceptional cases, these rocks may be capable of dressing to columns, if their divisional planes (of lamination or banding) are not easily separable, as is the case in many gneisses and schists. On the other hand,

if the rock can be easily parted along these planes, it may be possible to obtain thick slabs of stone.

The strength and durability of the quarried stone depends on the mineral components and their mode of aggregation. A rock with comparatively soft minerals—if these are interlocked with each other, as in marble of uniform composition—has greater cohesion, and is therefore stronger and more durable than one in which the hard mineral grains are uncemented and not interlocked, as is the case with some soft, friable sandstones.

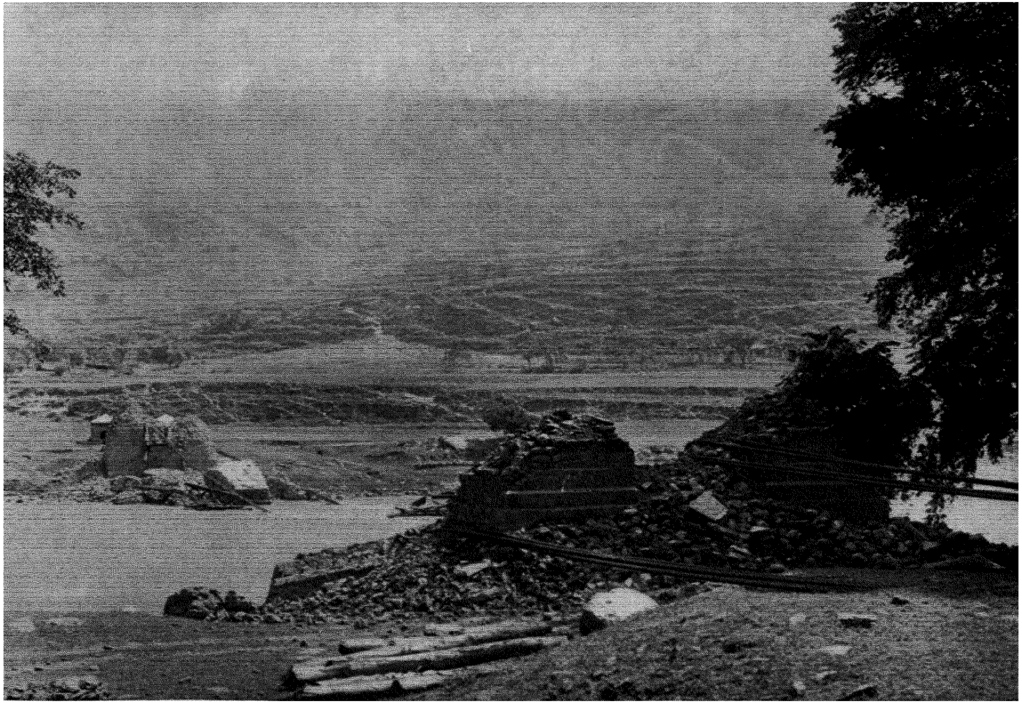
In addition to the strength of a rock, its porosity and weathering qualities are frequently of considerable importance—particularly under certain conditions. Frosts are liable to cause the disintegration of some porous rocks. If a porous rock is wet, and while in this condition is exposed to a severe frost, the expansive force of the ice which is formed in the interstices of the rock is liable to cause corners and sharp edges to break off and generally weaken the cohesion of the particles.

Important buildings which are to be fire-proof should naturally be built of those materials which are least affected by heat or great changes of temperature. Limestones or marbles are unsuitable for this purpose, because, when strongly heated, they are calcined to lime, which, on slaking, falls to powder. (See "The Imperfections of Marble," by Oliver Bowles in *The Quarry*, Vol. XXII, April, 1917, p. 79, taken from "Technology of Marble Quarrying," *Bull. No.* 106, *U.S. Bureau of Mines, Washington*, 1916.)

Hard sandstones or quartzites have a great coefficient of thermal expansion; consequently, when such material is exposed to fire, the expansion—besides loosening the joints and bonding—may result in such serious bulging of the walls as to cause a collapse of part of the building. Granite, if containing appreciable free quartz when exposed to great fluctuations of temperature, tends to become heavily fissured and disintegrated, due to the development of enormous internal strain. This, as explained in a previous chapter, is due to the great difference in thermal expansion of its principal minerals, quartz and felspar.

The exposed surfaces of rocks composed of relatively soluble constituents may, if used in buildings in manufacturing areas, be liable to severe corrosion by the acid vapours in the surrounding air. Many old houses or walls, etc., in London, which have been built of limestone, clearly show the effects of this corrosion.

Ornamental stones are usually chosen for their pleasing appearance; great strength and durability are not always considered as essential qualities, provided the stone is not unduly weak. However, as such



Per favour D.G.S.I.] FAILURE FROM FAULTY MATERIALS. [*Photo by C. S. Middlemiss.*

This suspension bridge was destroyed by an earthquake largely because boulders and pebbles were used as stone for masonry. The mortar did not hold in the smooth curved surfaces of the stone.

BUIN BRIDGE, KULU VALLEY (1905).

[*To face page* 110.

rocks are often placed in exposed positions, they should have good weathering qualities, and not become discoloured on exposure to rain and other atmospheric agencies. The presence of soluble salts such as gypsum or salt, or of minerals such as marcasite, which are liable to decomposition, should be sufficient reason for condemning an otherwise attractive stone. The alteration products are usually coloured oxides, etc., which result in the appearance of iron stains or other ugly patches on the exposed surface of the ornamental stonework.

LATERITE.—Laterite was the term applied by Francis Buchanan to the curious weathering product he met with on his travels in Malabar in 1800 and 1801. It is a kind of rock-rust, and represents the product left after a rock has suffered hydration and leaching of all its soluble constituents. It is scoriaceous to vermicular in structure, and very porous, and, where formed at the expense of granitic to granitoid gneissic rocks consists largely of the hydroxides of aluminium and ferric iron, with grains of quartz, which are clearly seen. This is Buchanan's type, a recent analysis of which shows 40 to 55 per cent. of silica, most of which (20 per cent.) is in the form of quart, 25 per cent. of alumina, 10 per cent. or more ferric oxide, 10 per cent. combined water, and the remainder largely of titania, ferrous oxide, lime, moisture and rarer constituents. In contrast with this, the laterite formed from basaltic and doleritic rocks, which themselves contain no free silica (except geodic material) show analyses as below: Silica below 3.5 per cent., alumina 45 to 58 per cent., ferric oxide, under 5 to over 25 per cent., magnesia, under 3 per cent., combined water up to 30 per cent., titania up to 15 per cent. occasionally, traces of lime and other constituents. The general colour and structure appears the same in both types of laterite, except that the grains of quartz are evident in the material derived from the granitic rocks. The real difference is clear in the chemical analysis that reveals so large an amount of combined silica. However, the mode of formation is similar, and has been fully described by the author in his book, "Bauxite and Aluminous Laterite," 2nd Edn., 1932. Where exposed to the weather, the rock laterite is hard, but within the mantle, especially in the Malabar coastal country, the laterite is soft, and can be cut with an axe-like tool into blocks for building purposes. These blocks harden rapidly with exposure, and make excellent material for all kinds of buildings, except, of course, dams for storage reservoirs. The blocks should not be quarried more than a few days before use if they are to be subsequently dressed. Laterite, under the name iron-clay and other terms, occurs in almost all tropical countries.

Owing to its porous structure, cappings or thick deposits of laterite generally hold large quantities of water, which often constitute

the source of supply for springs in laterite country. The rise and fall of the water level in laterite may be as much as 25 feet, so that it is certain that wells, if not sunk sufficiently deep, will become dry after a prolonged dry period. It is this rise or filling with water, and its subsequent draining away, that leaches the laterite of all soluble mineral substances, and thus leaves practically only insoluble matter —aluminium hydroxide and ferric hydroxide with residual quartz— as its chief constituents. It is thus a stone which is highly resistant to further weathering, and makes an excellent material where normal pressures and no abrasion is to be met. Great blocks of laterite have been used in the sea-walls of Marmagao harbour, for general building purposes, and also for road metal in Southern India. It is too soft for road metal on roads used by iron-tyred wheeled traffic, but it has the valuable property of becoming cemented into a concrete-like mass. Experiments with laterite powder and screened laterite fragments mixed with cement for a laterite concrete show that the blocks so made are astonishingly good, though somewhat porous. The concrete sets rather rapidly and hardens quickly, so that revetments can be speedily constructed or the foundations of important roads laid with expedition. The manufacture of high alumina cement or *ciment fondu* by the fusion of limestone and bauxite can be readily carried out by fusing limestone and aluminous laterite. So far as experimental work goes, the author has shown that *ciment fondu* made with Indian laterite and limestone can be made almost as cheaply as Portland cement, and yield a product which is as good, and in some ways (resistance to heat and evolution of heat when mixed with water) superior, to the European *ciment fondu*.

CEMENTS.—Although the term *Cement* is employed in civil engineering for the paste which is used as a binder for joining stone or brick masonry, or as a matrix in mortars and concrete, it is not restricted to any one type of such material, *e.g.* Portland cement. There are certain impure argillaceous limestones which, when calcined and slaked, reveal definite setting and hardening properties, and constitute the hydraulic limes and natural cements of many countries. Fine volcanic ejectamenta, such as the dust from Vesuvius and the tuffs of other areas, also possess, to some degree, setting and hardening characteristics, when suitably treated. This is also true of finely powdered brick or so-called *Surki.* According to some British writers, Roman cement was made from the nodules of chalk and clay found in the Isle of Wight, and commonly referred to by geologists as *septaria.* It is certain, however, that the Romans had already discovered the setting and hardening properties of the ash of Vesuvius. The name *Pozzuolana*, given to this class of cement, is taken from the

little village near Naples. The normal manner of using this volcanic ash is to mix it with slaked lime. Its composition alone averages—46 per cent. silica, 15 per cent. alumina, 14 per cent. ferric oxide, 10 per cent. lime, 3 per cent. magnesia, 4 per cent. water, and the remainder largely potash and soda. The *Trass* of the Rhine valley, a trachyte tuff, is also used with lime as a Pozzuolana cement. It averages 57 per cent. silica, 16 per cent. alumina, 5 per cent. ferric oxide, 4 per cent. lime, 1 per cent. magnesia, and 10 per cent. water with potash and soda. The pumiceous dust from Teneriffe, under the name *Tosca*, is similarly used with lime, and so also is the material called *Santorin* from the volcano of that name in Thera, one of the Grecian islands.

From what has been stated in the previous paragraph, it is clear that when a suitable material, such as hydraulic cement, is prepared, by calcining impure limestone, the setting and hardening properties must be due to reactions after water is added. The exact nature of these reactions is not fully known, but in the case of Roman cement (made from septarian nodules) and the original Portland cement of 1824 (made from impure limestones, by Joseph Aspdin) the *initial set* is thought to be due to the formation of hydrated calcium aluminate, while the *hardening* is ascribed to the liberation of an active calcium hydrate which cements the mass (and later probably combines with carbon dioxide ultimately to produce crystalline calcium carbonate). These reactions can scarcely influence the set and hardening of Pozzuolana cements, the original ingredients of which were quickly chilled from a molten condition and comminuted while still highly heated. It has long been known that if a mixture of silicates, such as $CaO.SiO_2$ and $2CaO.SiO_2$ be fused together and suddenly cooled in water (granulated), the latter silicate is decomposed, and the products, which consist of calcium bisilicate and calcium hydrate, swell up and produce a compact mass—the reactions being:

$$2CaO.SiO_2 + H^2O = CaO.SiO_2 + Ca(OH)_2$$

It is thought that these volcanic ashes and tuffs, as well as the basic slag cements, owe their setting and hardening properties to the above reactions. The slag cements are mixed and ground for use with slaked lime, and so belong to a true Pozzuolana type. The composition of a good slag cement (with lime added) is roughly from 49 to 52 per cent. lime, 22 to 30 per cent. silica, 11 to 16 per cent. alumina and ferric oxide, under 4 per cent. magnesia, less than 1.5 per cent. sulphur, and between 2.5 to 7.5 loss on ignition. Thus the ultimate composition is seen be to nearing that of Portland cement.

Portland Cement.—As already hinted above, the original Portland cement of 1824 was not unlike Roman cement. The name

given to it by Joseph Aspdin was because the hardened material resembled Portland stone—perhaps the most famous building stone of his day—a limestone quarried from the Upper Jurassic strata of England (see Photomicrograph No. 20). What we now know as Portland cement was the result of an almost accidental observation by I. C. Johnson of Swanscombe in 1845.

The composition of a typical modern Portland cement, as used in the construction of the newly opened Mettur dam, is given below.

Test Certificate of Government Test House, Alipur (Calcutta), made in 1931 on "Char-Minar" Brand Portland Cement.

	Results obtained.	Standard (1925).
1. Fineness of grinding, per cent.		
Residue on mesh 180 by 180	3.35	Not more than 10%
Residue on mesh 76 by 76 ..	0.02	Not more than 1%.
2. Chemical composition, %		
Lime..	65.24	
Silica..	22.02	
Alumina	5.61	
Iron oxide	2.09	
Sulphur calculated as SO_2..	1.52	Not more than 2.75 %.
Magnesia	1.74	Not more than 4.0%.
Loss on ignition	0.77	Not more than 3.0%.
Insoluble residue	0.99	Not more than 1.5 %.
	99.94	
Net proportion of lime to alumina	2.71	Between 2.9 and 2.0.
3. Tensile strength (neat) 7 days (average of six briquettes) lbs.	844	Not less than 600 lbs.
4. Tensile strength (cement and sand) 7 days (average of six briquettes) lb. (W_S)	540	Net less than 325 lbs.
28 days ditto	565	$W_S - \frac{10{,}000}{W_S} = 559$ lbs.
5. Setting time :		
Initial	2 h. 7 min.	Not less than 30 min.
Final	2 h. 58 min.	
6. Soundness	1 mm.	Not more than 10 mm.

The proportion of water used in gauging: (*a*) Neat briquettes, 23 per cent.; (*b*) cement and sand briquettes, 8½ per cent. Temperature during period of testing, 70 Fah. to 81 Fah.

Actually the composition of Portland cement varies somewhat if the products from different works all over the world are compared: The lime from 58 to 67 per cent., silica, 18 to 27 per cent., alumina, 5 to 10 per cent., ferric oxide, 0 to 7 per cent., magnesia, up to 3 per

cent., sulphur anhydride, up to 2.75 per cent., and the alkalies up to 2 per cent. The British Standard Specifications lay down that:

The proportion of lime to silica and alumina shall not be greater than the maximum nor less than the minimum ratio (calculated in chemical equivalents) represented by CaO : SiO_2 plus Al_2O_3 as 2.85 : 1 or 2 : 1 respectively. Loss on ignition not to exceed 3 per cent., SO_3 less than 2.75 per cent., magnesia not above 3 per cent., and the insoluble residue under 1.5 per cent. (see Standard (1925) in the above test certificate).

The mode of preparing Portland cement, by the modern wet process and burning in a rotary kiln, is so well known that it is unnecessary to describe it in a work of this nature. Great strictness is necessary, both in regard to the quality of the limestones and clays used, and also on the degree of grinding in preparing the slurry. The temperature and duration of burning, and the final pulverisation of the clinker, are all maintained with care. The burning temperature is about 1,425° C.; the colour of the product is grey; it has a specific gravity of roughly 3.15, which is higher than most cements, and useful for detecting dilution. As already stated, the reactions of setting and hardening are not absolutely known, but it is clear from an acid test that calcium hydrate or calcium carbonate is present *free* in the masonry mortar where Portland cement was employed. This explains why such cements are slowly dissolved in pure, and attacked by salt waters, and explains why they cannot be resistant to fire—their composition renders them vulnerable. Nevertheless, Portland cement is recognised as the finest general cement for most engineering works, and is used in enormous quantities (see remarks on the Mettur dam on page 235). In Ferro-Portland, Iron-ore and Iron cements the main composition is that of Portland cement, except for a variation in the amounts of ferric oxide and alumina—the former being increased to over 8 per cent. and the latter being reduced to nearly 1 per cent., and the specific gravity is greater, nearly 3.3. The object of adding the ferric oxide was largely to render the cement more resistant to sea water, but it is doubtful if this result has been attained. So much stress has been given to the composition of Portland cement and its acceptance by the public because of its conformity to the British Standard Specifications, that attention is now specially drawn to its high percentage of lime and the remarkably low percentage of alumina. In this respect Portland cement is entirely different (in chemical composition) from the so-called High Alumina cements which are described in the next paragraph.

CIMENT FONDU.—The first patent for the manufacture of high alumina cement appears to be that of M. Bied (France) in 1908, but

since then there have been several, including one by the author in 1932 (Indian Patent, Specification No. 18911, dated 27th April, 1932, "Improvements in or relating to the Manufacture of Cement and the Recovery of Iron in such Manufacture"). The cement may be made by the fusion of limestone and bauxite or aluminous laterite or simply by heating a powdered mixture of these components for a sufficient time. The fused material or slag, cooled slowly, and this crystalline material crushed and powdered yields the superior product. It is known as *ciment fondu* or fused cement, and the British Standard Institution have in hand a Specification for this type of high alumina cement (*The Structural Engineer*, November, 1930). The subject of high alumina cements has been very ably dealt with by N. V. S. Knibbs in his book "Industrial Uses of Bauxite," pp. 70–91, 1928. The composition of this class of cements varies between the following limits: 44 to 36 per cent. alumina, 44 to 39 per cent. lime, 5 to 10 per cent. silica, 8 to 10 per cent. ferric oxide, and the remainder largely titania, magnesia, etc. The chief advantages claimed for this fused class of cement, or *ciment fondu*, are that it is practically immune to the attack of salt or sulphate waters; is definitely fire-resisting; has a slow initial set (2½ to 4 hours) and then hardens very rapidly, attaining in 28 hours a greater strength than Portland cement in as many days, and continues to have a higher tensile and compressive strength than Portland cement. Its disadvantages have been that it costs about twice to three times the price of Portland cement and has not had a British Standard Specification to recommend it to non-technical users. Both these drawbacks should shortly be removed—the former by smelting laterite with limestone in a blast furnace and recovering a high alumina slag with pig iron as a by-product, and the latter by the issue of a Specification under the auspices of the British Standards Institution.

The following tests by the Government Test House, Alipur (Calcutta) on samples of *ciment fondu* prepared by the author in 1933 by the fusion of aluminous laterite and limestone are useful for comparison with the high grade Portland cement mentioned on page 114 as utilized in the construction of the Mettur dam.

	Results obtained.	
Fineness of grinding :		
(Slag 4) residue on mesh 170 ..	3.15	Average of six.
residue on mesh 72 ..	0.10	„ „
(Slag 6) residue on mesh 170 ..	2.50	„ „
residue on mesh 72 ..	0.04	„ „

Chemical composition (No. 6) :

Lime	36.20%	
Silica	8.40	
Alumina	44.30	
Iron oxide	4.50	
Magnesia	0.90	
Titania	6.20	
Sulphuric anhydride	trace	
Loss on ignition	gain	—0.5%
Insoluble residue		Amount insoluble in hydrochloric acid, 11.6%, of which the silica is 8.4%.
	100.20	

	No. 6	No. 4.
Tensile strength (No. 6) 1 cement to 3 sand by weight average of six after one day	428 lbs.	450 lbs.
„ two days	495 „	461 „
„ three days	543 „	417 „
„ a week	575 „	440 „
„ 28 days	664 „	534 „
„ three months	767 „	645 „

Setting time (No. 6) :

		No. 4.
Initial set	21 min.	21 min.
Final set	10 h. 8 m.	6 h. 34 m.
Soundness (No. 6)	½ mm.	½ mm.

Heat resistance :

	No. 6.	No. 4.
1 cement : 3 sand, after heating to 1,000° C., cooled to 400° C. and quenched ..	440 lbs.	320 lbs.

briquettes after quenching were found to be free of visible cracks, but of slight reddish colour.

It should be pointed out that these cements are grey in colour and only a little darker than Portland cement, but the shade can be readily modified as it can with Portland. It was not discovered till afterwards that the samples had been contaminated with sodium carbonate so that the heat resistance is all the more remarkable.

PRESERVATION OF BUILDING STONE.—It is necessary to state that no preservative will save a stone face from scaling or becoming friable if the rock itself is subjected to a greater stress than it can safely bear. On the one hand, the rock used in a building may be a decomposed variety of the type required, and which, in consequence, is crushed; on the other hand, if the stonework is exposed to great alternations of temperature and the rock consists of minerals of different coefficients of thermal expansion, it is evident that the only remedy is to plaster the facing—in which case, the use of brick might have saved the expense of dressing the stone. The appearance of an efflorescence from internal sources has already been treated in the section on Building Stone (page 107).

Preservatives may prevent a rock surface from absorbing moisture, and subsequently "peeling" as a result of frost action. In other cases, the rock surface may be hardened against the solvent action of rain water carrying deleterious chemical compounds. In some instances, if the preservative is used in the process of building, it may be possible to prevent the occurrence of an efflorescence on the wall faces. However, in most cases, the extra recurring cost of the preservative might have been saved if the stone had been previously examined and more suitable material chosen.

The merits and limitations of the various preservatives—paint, water-glass, and the numerous other substances—are familiar to the engineer. His experience in their use will probably be the best guide in making a choice.

The following reference may be useful to an engineer who is faced with the problem of the preservation of a building or monument:

(1) "Removing Stains from Stonework," *The Quarry*, Vol. XX, 1915, p. 242. Use of soft water and common laundry soap. Boil until the soap is dissolved; add fine white sand until of the consistency of putty; while mixing add 5 tablespoonsful of ammonia per bucket of water; scrub surface with help of brush, and wash down with a hose.

(2) "Cleaning Stonework," *The Quarry*, Vol. XXV, October, 1920, p. 290.

(3) "Preservation of Stone," *The Builder*, for 15th October, 1920. Chief agencies of destruction in atmosphere are (1) Carbonic acid, (2) Sulphuric acid, and (3) Frost.

(4) "Preservation of Stone"—extract in *The Quarry*, Vol. XXIV, March, 1919, p. 78.

(5) "The Preservation of Stone," by Noel Heaton, *The Quarry*, Vol. XXVII, February, 1922, pp. 56.61. Heaton considers the order of durability as:

(1) Granite.
(2) Siliceous limestone.
(3) Magnesian limestone.
(4) Limestone.
(5) Calcareous sandstone.
(6) Ferruginous sandstone.

Page 57.—" The properties demanded of a perfect stone preservative are many and conflicting, and may be briefly tabulated thus :

(1) It must penetrate easily and deeply into the stone, and remain there on drying.
(2) It must not concentrate on the surface so as to form a hard crust, but at the same time harden sufficiently to resist erosion.
(3) It must prevent penetration of moisture, and at the same time allow moisture to escape.
(4) It must not discolour or in any way alter the natural appearance of the stone.
(5) It must expand and contract uniformly with the stone, so as not to cause flaking.
(6) It must be non-corrosive and harmless in use.
(7) It must be economical in material and labour of application.
(8) It should retain its preservative effect indefinitely."

Page 58.—" The principles on which they act can be roughly grouped as :

(A) Those which only act as surface coatings, *e.g.* limewash.
(B) Those which impregnate the stone without chemical action on it, *e.g.* wax in benzene.
(C) Those which operate by chemical reaction with the stone, *e.g.* baryta for H_2SO_4 (interiors), water-glass and magnesium fluosilicate."

Page 61.—" Conclusions.

(1) New work can be rendered to a certain extent more resistant to decay by treatment with fluosilicate, provided the strength of the solution and method of application is adjusted to suit the stone used.
(2) No preservative treatment will be effective on faulty or face bedded stone.
(3) Constructional methods of reducing decay (prevention of damp, effective carrying away of storm water, etc.) are more important than preservative treatment.

(4) For outside work on old buildings no preservative at present known serves to preserve decayed stone for more than a limited period. The most economical treatment is dressing with soft soap and alum, renewed every few years.
(5) For interiors, where the stone has been corroded by sulphur compounds, baryta treatment is, in many cases, beneficial, and should be followed by distempering.
(6) Preservative treatment should only be employed where it is certain that it can, at the worst, do no harm. For this reason, articles of unknown composition should be avoided, and only materials used the action of which is well understood."

Hume (" Geology of Egypt," Vol. I), quoting Lucas in regard to the spalling produced by the evaporation of salt containing waters in walls of buildings in Cairo, says :

" In the case of walls that have been plastered, the plaster is frequently forced bodily away from the wall, and in between the wall and the plaster a sheet of almost pure sodium chloride, sometimes one or two millimetres in thickness, was found. In other cases small cavities in the mortar or in the stone were filled with a powdery mass of crystals of almost pure sodium chloride."

He ascribes these defects as due to the following factors : (1) presence of moisture ; (2) degree of porosity of the stone ; (3) presence in the ground or in the stone of salts readily soluble in water ; (4) opportunity for the salts to crystallise out by the evaporation of the water holding them in solution. The same phenomena were noticed in the Ma'aza Limestone Plateau (Eocene) in Upper Egypt. This modular limestone contains sodium chloride and spalls and crumbles to such an extent on cliff faces that such features are unscaleable.

Professor A. Beresford Pite, humorously and extravagantly writing in *The Observer* of 23rd August, 1925, says :

" Ever since the magnesium limestone, of which the New Palace at Westminster is built, was first exposed to the chemical constituents of the London atmosphere, it has been slowly and surely transformed into some sort of a heap of Epsom salts. The fumes of the potteries on the Lambeth bank of the river, next door to the Archbishop, which ascend from their chimneys and kilns, descend in a gentle but pervading rain of dilute sulphuric acid upon the pile of exposed magnesia at Westminster, with demonstrable results."

Elsden and Howe (" The Stones of London," 1923, p. 81), discussing decay due to magnesium sulphate, say :

" A good example is seen in the stone, magnesian limestone from Anston which has been used in the Houses of Parliament, Westminster . . . the $MgSO_4$ has been formed by the town atmosphere (sulphurous and sulphuric acid)—and it is readily soluble, and consequently readily removable by rain from exposed surfaces—in those places where the moisture hangs some time the deleterous solution has time to penetrate, so that when a spell of dry weather follows the moisture is evaporated and $MgSO_4$ crystallises—this it does with disruptive effect."

A. P. Laurie (*Jour. Chem. Industry*, 27th February, 1925), discussing the influence of calcium sulphate in promoting stone decay, says :

" There are many recognised causes of stone decay, such as wind erosion, expansion and contraction with changes of temperature, the freezing of water within the pores of the stone, and the slow solution of calcium carbonate in water containing carbon dioxide, and recently Professor Marsh has suggested the possibility of bacterial attack. In addition to these, we have under modern conditions the conversion of calcium carbonate into calcium sulphate. Sulphur dioxide in presence of air and moisture converts calcium carbonate into calcium sulphate, and in addition sulphuric acid, sulphurous acid, and ammonium sulphate dissolved in rain water react with calcium carbonate to produce calcium sulphate."

" The breaking up of a stone by the formation of calcium sulphate crystals has been attributed to the fact that, equivalent for equivalent, the calcium sulphate crystal occupies a larger volume. But I do not think this is the main cause. When a stone breaks up owing to the crystallization of calcium sulphate, the crystals form freely along certain layers or in pockets in the stone. It is the persistent growth of the crystals in certain layers or pockets which ultimately breaks up the stone. The reason for the selection of these particular areas for crystal growth is somewhat obscure, but there can be no doubt that it takes place. There also seems to be in a stone something corresponds to the water level in a soil."

The same writer gives the following analyses of the oolitic limestone used in the building of Lincoln Cathedral, and shows (1, 2, and 3) that the fresh stone contains practically no sulphate that the stone surface *inside* the Cathedral (4, 5, 6 and 7) have been effected by the SO_3 given off by the gas (lighting) and coal (heating) used in the building, and that the stone surface *outside* the Cathedral has either absorbed less SO_3 (8, 9, 10 and 11) or that much calcium sulphate has been washed off in weathering.

Dealing with the subject of " Stone Decay and the Preservation of Buildings " (*Jour. Chem. Industry*, 27th February, 1925), A. P. Laurie,

after discussing the formation of calcium sulphate in various stones, says:

"The question next arises what can be done to improve the durability of the stones which break . . . at this stage it may be of interest to say something about silicon ester . . . as a cementing material to re-cement together the loose, rotten surfaces of valuable carvings, etc. I was satisfied from preliminary experiments and observations that anything which closed the pores of the stone was dangerous and apt to cause flaking. What I felt was required was something corresponding in properties to a thin glue which, soaking freely into the stone, would then dry and leave the particles of the stone with a thin cementing layer round them and the pores open. Finally I found it in silicon ester, which is prepared by the action of alcohol on silicon tetrachloride. It is a liquid which mixes readily with volatile solvents, and when exposed to the air and moisture deposits hydrated silica in transparent layers.

"I suggest a complete change of policy with regard to our public buildings—namely, that we should assist the rain by washing them down in the summer so as to ensure quick evaporation, allowing them to dry out, and washing them again two or three times. An example in favour of this method is to be seen in the Goldsmiths' Hall, built early 19th century of Portland stone, which at any rate for the last 30 years has been washed down with the fire-hose some two or three times a year. Whether it would be safe to wash down the stones inside the building is more questionable. A great deal can be done replacing gas by electric light and introducing scientific methods of heating. The treatment of soft surfaces like Church stone and decaying surfaces with a thin solution of *silicon ester* will do a great deal to preserve and protect stones."

	1	2	3	4	5	6	7	8	9	10	11
Water	0.6	0.4	1.0	1.30	1.30	1.50	1.10	0.90	0.80	0.60	0.90
SiO_2 Insol. in HCl	1.1	4.7	2.3	2.90	2.70	3.00	2.80	4.00	2.80	3.00	2.80
Fe_2O_3 / Al_2O_3 }	2.2	4.8	2.6	7.30	8.60	4.90	5.40	1.70	2.60	2.70	2.60
CaO	53.7	49.7	51.9	46.54	46.05	49.67	49.67	50.23	51.01	51.29	51.40
MgO	Nil	0.6	0.6								
CO_2 carbon anhydride	42.3	39.7	41.5					41.20	41.80	41.70	41.80
SO_3 sulphuric anhydride	.01	Nil	Nil	2.54	2.40	2.19	1.44	1.58	0.58	0.30	0.27
$CaCO_3$	96.0	88.7	92.7	79.92	79.23	85.96	86.91	87.73	90.37	91.21	91.44
$CaSO_4$	0.17	—	—	4.32	4.08	3.72	2.44	2.68	0.98	0.51	0.46
$MgCO_3$	—	1.26	1.26								
CO_2 in excess				4.24	4.07	0.68	1.16	2.60	2.04	1.57	1.57

Fresh Stone.—1, Silver bed sample from quarry; 2, White; 3, Red.
Inside Stone.—4, 0 to ¼″, distances from facing; 5, ¼ to ½″; 6, ½ to ¾″; 7, ¾ to 1″.
Outside Stone.—8, 0 to ¼″, distances from facing; 9¼ to ½″; 10, ½ to ¾″; 11, ¾ to 1″.

PART II

FIELD OPERATIONS

CHAPTER VII

THE EARTH'S MACHINERY

THERE is a popular idea that the earth's crust is relatively thin, and that it bends almost under the weight of a large building, because it is underlaid by molten basalt. From this it has been assumed that mountains must have sub-crustal protuberances into the molten material below of the same relative proportions as is found in icebergs —the visible height barely one-tenth the root. And it has followed that the removal of material from the mountains by denudation must unload them, and so cause them to rise. Similarly, alluvial plains and deltas, on which sediment is being deposited, are being loaded, and tend to sink. When two such areas are adjacent, a line of shear develops between until dislocation finally occurs, and thus produces a fault. Continued movements along this fault zone must occur so long as erosion and deposition continue to cause uplift and subsidence on opposite sides. These periodic slips in the plane of faulting are believed to give rise to most earthquakes. The belief in the existence of the " roots-of-mountains " was upheld by some data which indicated that acid rocks (granites, etc.) had considerably higher fusion temperatures than basic rocks (basalts, etc.). The conceptions given above have answered as a working hypothesis for many observed facts, but there are other data which appear very serious as evidence against the assumption of a permanent molten sub-crustal layer. Radioactivity is now not regarded as providing more heat than the earth loses continually. Seismograph records and their study have convinced mathematicians that the earth is solid at least to a depth of 1,800 miles. Finally, the scrutiny and determination of the melting temperatures of various rocks and related substances make it evident that the acid rocks have the lowest melting points—hence the deep roots to mountains become impossible. In this chapter an attempt is made to give an outline of the views held by geophysicists and geologists to-day.

COMPENSATION.—The *pull* or attraction between the masses of a mountain, *e.g.* Schiehallion, and a plumb line was used by Professor Maskelyne about 1772, in ascertaining the mean density of the earth.

The idea had been suggested by Sir Isaac Newton many years before. The result attained was 4.71, as against 5.60 now generally accepted. Nearly 80 years ago, when Colonel Everest had extended the Great Indian Triangulation Survey into North-Western India, a discrepancy was noticed which was too large for observational errors. It was found that the difference of latitude between Kaliana and Kalianpur, as determined by triangulation, was not the same as the difference in the latitude of these places as ascertained by astronomical methods involving the use of a plumb line. The discrepancy was 5.236 seconds, and it was naturally concluded as due to the *pull* of the Himalayas distant 60 miles from Kaliana. The problem was subjected to direct calculation by Archdeacon J. H. Pratt of Calcutta, who discovered that the supposed discrepancy due to the Himalayan *pull* was really only one-third of what it should have been. This next raised another question—why is the *pull* so much less than the calculated amount, or how the mountains came to be so largely compensated? Sir George B. Airy, then Astronomer Royal, gave an interesting explanation of the facts discovered by Pratt, but with which theory Pratt did not agree. (*Phil. Trans.*, **145,** 53.100, 101.104, 1855; **149,** 745.778, 1859; also *Geol. Mag.*, **65,** 280, 1928.)

Airy's theory—known as the "Roots-of-Mountains" theory—is very favourably discussed by Jeffreys, who states:

"His theory is practically that developed here; he considered the earth as having a thin solid crust, supported on a weak, but not necessarily fluid, substratum, and showed that the elastic resistance of the crust to bending might be so small that any extra load added would push the crust down until the load was balanced almost wholly by the upward pressure of the material below. The smallness of the disturbance of gravity due to the visible surface topography follows as a natural consequence. Airy remarks, indeed, that Pratt's results ought to have been anticipated, for the notion of a crustal layer with a magmatic substratum was a familiar one at the time."

And as regards the hypothesis put forward by Pratt, he says:

"Pratt proposed the alternative hypothesis that the development of surface features is due to the vertical expansion of columns of rock down to a certain uniform depth; the expansion is the same at all points of the same column, but differs from one column to another. There is no change of mass within any column, and therefore the smallness of the disturbance of gravity agrees as well with this theory as with Airy's."

William Bowie (*Pres. Add.*, *Jour. Wash. Acad. Sci.*, 21, No. 6, 19th March, 1931) thus briefly states these rival theories:

"There has been much discussion in literature on isostasy of the question as to whether the Pratt or the Airy hypothesis is the true one. Pratt postulated that the densities vary under different classes

of topography. Under the oceans the density would be abnormally great, and under the continents it would be abnormally small. Airy, on the other hand, suggested that the depth of compensation is very irregular, and that crustal masses under the continents extend much further below sea level than do such masses under the oceans. Under mountain areas these protuberances would be greater than under plateaus and valleys. We have not yet been able to prove which of the two hypotheses is the true one, since the application of either of them to gravity and deflection data gives about the same satisfactory results."

Walter H. Bucher, in his very lucid book—" The Deformation of the Earth's Crust," 1933, p. 40—discusses this matter also.

" *Pratt versus Airy.*—Having arrived at a concept of the earth's crust which seems consistent with geophysical knowledge, we must turn to the two conflicting ideas concerning its physical behaviour which underlie the successful gravity computations of Hayford and Heiskanen.

" Hayford postulates that the physical behaviour of all parts of the crust is essentially the same. An earth-column undergoing deformation in the centre of the Pacific Ocean behaves essentially like a column in the heart of Asia. The heavy and therefore low-lying column behaves like the light, and therefore high column. Changes in height are somehow accompanied by changes in the average density; yet in their physical behaviour the two columns do not differ materially from each other. This concept was first voiced in 1855 by J. H. Pratt.

" Heiskanen's method is based on the ideas of G. B. Airy, which were published simultaneously with Pratt's paper. He pictures the crust as made up of two parts of constant average density, but of different strength. The upper part has lower density and higher strength, that is, it is capable of resisting form changes even at depths greater than the average thickness of the crust. The lower part possesses higher density and lower strength, that is, it tends to flow more readily. Columns of different height do not differ in average density, but in thickness. Because of the greater strength of the lighter material, it can be forced down into the asthenosphere and, holding its shape, is buoyed up in it. The higher a column projects above the level of the ocean bottom, the deeper immersed its roots must be to maintain equilibrium. This hypothesis correspondingly has been called the ' roots-of-mountains " hypothesis. . . . It is obvious that from gravity data alone we cannot expect sufficient evidence to decide which of these two alternative views corresponds to reality."

These theories, given in the words of a mathematician, of a geophysicist, and of a geologist, respectively, form the basis of our ideas concerning the probable structure of the earth's crust. Both theories were advanced by mathematicians and, besides accounting for gravity anomalies, *i.e.* the difference between the value of gravity obtained by measurement (Gm) and (less) that computed (Gc), they indicate a condition of perpetual balancing of masses in the outer shell of the earth.

ISOSTASY.—C. E. Dutton, in an address " On Some of the Major Problems of Physical Geology " (before the Philosophical Society of Washington, in 1889; *Bull.*, Vol. II, pp. 51.64), coined the word *Isostasy*, although, as Jeffreys has stated, some writers prefer the name " *Compensation* to denote the fact of approximate uniformity of mass over the earth within vertical columns of the same cross-section extending down to a standard equipotential surface, and restrict 'isostasy' to the physical process that leads to the establishment of this state." It is of interest to record that Dutton expressed his view on the mechanism involved as follows: " Where great bodies of strata are deposited, they progressively settle down or sink seemingly by reason of their gross mechanical weight, just as a railway embankment across a bog sinks into it." Bowie expresses the popular idea by saying: " . . . The primary causes of at least the major changes of the earth's surface are evaporation, precipitation, erosion and sedimentation." But Bucher ascribes a secondary place to the effects of erosion (unloading) and sedimentation (loading) to account for the formation of geosynclines (belts of subsidence) and the uplift of mountain ranges.

" We must, therefore, look below the surface for the factors that control the shifting fates of the face of the earth. In doing so, we must not forget, however, that the isostatic behaviour is a reality, causing all changes in the distribution of rock materials to be followed by changes in elevation so far as they tax the crust beyond its strength. But isostasy does not create, it only modifies."

E. A. Hodgson in a recent paper (" The Earth Beneath in the Light of Modern Seismology ": *Ann. Rept. Smithsonian Institution*, 1931) has given an excellent summary of the prevailing views in regard to the structure of the earth. Fig. 8, which is taken from his paper, shows this diagrammatically, while the table below, based on the ideas put forward by J. Barrell (*Jour. Geol.*, Vol. XXIII, p. 44, 1915), represents the opinions we hold regarding the relative strength of the rock in the outer shell of the earth:

	Depths in Kilometres	Percentage Strength	Layer of Shell
Lithosphere (Rock zone)	0	100	Granite
	20	400	
	25	500	Basalt
	30	400	
	50	25	Dunite
Asthenosphere (Weak zone)	100	17	
	200	8	Middle Shell
	300	5	
	400	4	

There is no suggestion that the Asthenosphere, which is thought to be at least 600 kilometres thick, is anywhere fluid, but it is weak enough to bend or be distorted easily. Further, the idea of an absolute liquid layer at the base of the Lithosphere is not accepted by any geologist familiar with the evidence from earthquake records. Professor J. Joly ("The Movements of the Earth's Surface Crust": *Philo. Mag.*, 6th Ser., Vol. XLV, 1923, and "The Surface History of the Earth," 1925) has, taking Airy's interpretation of gravity anomalies, propounded a really inspired hypothesis, based on accumulation of

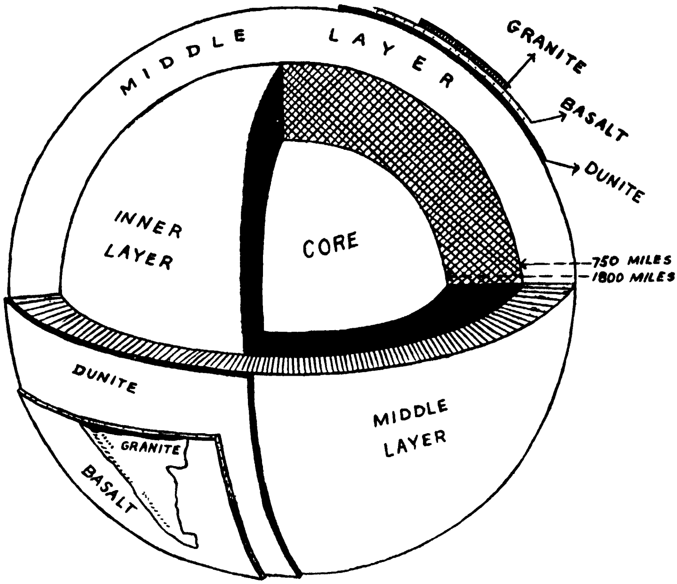


FIG. 8.
Structure of earth.

heat from radioactive sources, to provide periodic melting (every 50 million years) of the basalt layer. Unfortunately the theory falls to the ground on an inadequate supply of heat. It may be safely said that theories based on a molten layer above the core are faced by the evidence of seismograph records against such a possibility. Neither Pratt's nor Airy's hypotheses would be accepted if this was a primary assumption, and though there are many who consider that a molten layer is an essential part of at least Airy's original roots-of-mountains theory, this is denied by Jeffreys.

The engineer as well as the geologist wants to know the cause of these earth movements—earthquakes, volcanic eruptions, mountain uplift and areas of subsidence. The evidence from the Ganges delta shows that subsidence has kept step with deposition of silt until over 500 feet of sinking without transgression by the sea has occurred in

this region. Charles Schuchert has shown that thousands of feet of strata have accummulated in some ancient geo-synclines which persisted for long geological periods before any folding movements took place. The causes of uplift and subsidence, of mountain formation and geo-synclinal depression, while involving erosion and sedimentation, are of deeper origin than surface action. Jeffreys is quite definite that loss of heat from the interior of the earth is the prime cause, because it must produce contraction of the upper layer, which requires adjustment by the outer or crustal layer. With this general view Bucher clearly agrees, although he details elaborately the mode of deformation that must be imposed on the crustal layer. He shows with reasonable arguments that the material of the upper layer—the granite and the sediments—must be often driven downwards as a result of under thrusting. He draws attention to the fact that the crust is subject to periods of tension as well as the expected compression —and this every geologist knows. And he says (" The Deformation of the Earth's Crust," 1933, p. 477) :

" Our reasoning has led to the following five hypothetical conclusions, of which the first four are of fundamental importance :

(1) There is a relatively strong crust overlying a relatively weak asthenosphere.
(2) The crust is strong enough to transmit tangential stresses which are the chief cause of crustal deformation ; it is weak enough to tend toward isostatic equilibrium.
(3) The crust is subject alternately to tensile and to compressive stresses, caused by alternating swelling and shrinking of subcrustal matter.
(4) Fluctuations in the heat content of the subcrustal body of the earth constitute one of the factors which control the alternating contraction and expansion of subcrustal matter.
(5) Since archæozoic time the heat content of the crust has decreased materially."

" The Machinery of the Earth " was chosen as the subject for a lecture before the Institution of Mechanical Engineers by the late Professor J. W. Gregory (Thomas Hawksley lecture, 7th November, 1930), and in this he stated that : " The contraction of the earth may be accepted with confidence, since so distinguished a mathematician as Dr. H. Jeffreys (" The Earth," 2nd Edn., 1929, pp. 29.34) rejects emphatically the arguments that have been advanced against it." In his chapter on Isostasy, Jeffreys has discussed in detail : (1) The behaviour of matter under shearing stress ; (2) the subject of permanent set ; (3) plasticity and strength ; (4) definitions of solids and fluids ; (5) the properties of solids ; (6) the probable mechanical properties of the earth's crust ; and (7) compensation. His analysis

is both complete and convincing, and his summary is as follows (*supra*, p. 202):

" A classification of the mechanical properties of matter in the solid and liquid states has been given. The apparent small gravitative effect of mountains is explained on Airy's lines as due to the squeezing out of a weak but dense substratum by the weight of loads added on top. It is shown that compensation distributed uniformly down to a definite depth would be consistent with Airy's mechanics, but that with the actual structure of the crust compensation is probably concentrated at the bases of the granite and intermediate layers. It appears that a widespread visible inequality more than about 700 metres in height would lead to fractures in the lithosphere, and that great mountain ranges must be bounded by fault planes and supported by hydrostatic pressure, and not by the strength of the lithosphère. The outstanding residuals seem to point to a strength in the lower layer of the order of 10^8 dynes/Cm^2 (*per square centimetre*), say one-eight that of granite at the surface."

The words in italics are mine. The extracts and statements in the foregoing pages should provide the reader with material for thought, and the references will give him the means of investigating the subject further.

CRYSTALLISATION.—This is becoming an important subject. It probably holds the key to many important problems which concern the working of the earth's machinery. It is well known that matter in a crystalline form is denser or occupies less space (volume) than the same matter in an amorphous condition. For example, opaline or colloidal silica (Opal) has a specific gravity of 1.9 to 2.3, whereas crystalline silica (Quartz) has a specific gravity of 2.4 (Cristabolite) to 2.65 (Quartz). As a rough analogy, we may compare the amorphous material to a tumbled heap of bricks and the crystalline condition to a neat stack of similar bricks. Even a neat stack of bricks may be constructed with different arrangements of the bricks so as to give different shapes to the stack as a whole—*i.e.* a cube, a pyramid, etc. And so in the crystalline mineral calcite we may have a six-sided flat-ended prism, or a six-faced prism with a pyramid top (either elongated as in *Dog Tooth spar*, or flattened as in *Nail Headed spar*), or even a rhomb-shaped crystal (as in *Iceland spar*). Again, one substance may occur, under different conditions in different crystalline forms—thus the aluminium silicate Al_2SiO_5, Sillimanite (Fibrolite), with a specific gravity of 3.2 and a hardness of 6 to 7, may occur as the orthombic mineral Andalusite, which has a specific gravity of 3.18 and a hardness of 7.5, or as the triclinic mineral Kyanite (Disthene) which has a specific gravity of 3.6 and a hardness of 7.

The points to which attention has been drawn in the previous paragraph will increase in significance when it is remembered that

quartz can grow in perfect crystals in soft clayey material, such as kaolin or saline marls, if there is an excess of silica present and the material is damp (moist). Quartz crystals may grow in fissures (mineral veins) due to waters carrying silica, and which are not even hot in temperature—in fact quartz cannot be formed as such above a temperature of 800° C., or perhaps lower. This has led to the idea that since granites and pegmatites contain crystalline silica in the form of quartz, these rocks must have been formed at a lower temperature than 800° C. In the case of many mica-bearing pegmatites, containing quartz and feldspar, chiefly, with prisms of beryl (in the quartz) and large crystals of garnet (in the feldspar), which the author studied closely, it seems doubtful if the minerals formed above the critical temperature of water (360° C.). However, it is well established that calcite crystals have grown in mineral veins, and also that crystalline calcite may form in an igneous rock (*i.e.* from a fluid magna) like dolerite. This is also true of the mineral iron pyrites. Cubes of brassy pyrites can form in soft clays and are found in slates. Pentagonal dodecahedral of brassy pyrites occur in the micaceous hematite of the Great Rock Mine, Hennock (Devon). Pyrites appears to be an original mineral in granites and in dolerites and other igneous rocks.

A moment's consideration now shows us that crystals may grow in a liquid (*e.g.* salt when brine is slowly evaporated), or in a thick fluid (*e.g.* sugar crystals in vegetable marrow jam), or even in a solid (*e.g.* gypsum in pyritic clays when penetrated by water carrying lime or calcium carbonate). The vitrification, or so-called de-vitrification, of ancient glasses indicates this type of crystallisation in a solid condition. Further, the forces which accompany crystallisation may be considerable. The freezing (crystallisation) of water can cause a lead pipe to burst and to split rocks, as well as produce over-riding at the banks when a pool or lake freezes. A porous pot or a porous rock can be disrupted by growing crystals of copper sulphate in the pore spaces (by allowing the solution to percolate through and evaporate slowly at a surface). But all these examples, while showing how readily crystallisation may occur under suitable and very different conditions, are, probably, quite insignificant when compared with crystallisation which occurs under great pressure and at relatively high temperatures, say, 10 miles, down in the earth's crust. The substances involved will tend to occupy the smallest volume, or to adopt new combinations which produce minerals of greater density. These effects, which influence molecular particles, when taken in terms of cubic miles, must become very important factors in questions of regional subsidence or elevation. Compression, or the formation of dense minerals, assists

surface subsidence, whereas release of pressure, and re-transformation, must assist uplift.

As already stated, this subject—especially the aspects mentioned in the last sentence of the previous paragraph—has not been adequately examined. There is accummulating evidence to show that simple rocks like limestones are not only transformed into marble, if subject to sufficient pressure, but may become calc-gneisses under intense squeeze. And there are numerous exposures of granites which are so curiously associated with sedimentary beds as to be suggestive, not so much of igneous intrusions in the latter, but to their *crystallised* (crystalline) representatives. If it can be definitely proved that the granitic cores of mountain ranges are really crystallised sedimentary or other rocks which have been subject to enormous squeeze, then we will have the key to further examples of relief (adjustment of forces) by a re-arrangement of the particles (so as to free themselves of the compression). We may even have the key of the whole subject of crustal movement which follows from adjustments of volume due to cooling. This cooling, due to the steady loss of heat from within the earth, appears to be the true secret of the cause of crystallisation deep within the crust. Thus begins the initial subsidence of the surface. This subsidence of the outer crust which leads to crustal buckling brings in its train all the complications of geosynclines and mountain belts and the folding and faulting found in each of those zones.

TECTONIC MOVEMENTS.—There is evidence in almost every country to show that slow changes—of subsidence or elevation—are in progress. It may be the presence of a submerged forest in the sea, or raised sea beaches on the shore. That such movements have been active in past geological epochs is seen by the discovery of strata with marine fossils in what is now mountain country, such as the Alps, the Himalaya, and similar chains, and the examination of still other areas, such as those of the Southern Uplands of Scotland, and other classic localities, reveals marine fossils in greatly contorted and sheared rocks. These examples, and there are hundreds like them, relating to rocks of every geological epoch, are of interest to the geologist, in that they supply data for tracing the changes of the distribution of land and sea in past ages. They are of importance to engineers, if a large scheme such as canal, great docks, or even an important bridge, is to be constructed. For example, in the case of the Suez Canal it might be of very great advantage to this important highway for ships if the area is slowly sinking, whereas it would be a troublesome outlook for the future if the region was steadily rising. The geological history of the Panama region is thus of great interest also. It would appear that the Isthmus of Panama first rose from beneath the sea as an archi-

pelago of islands, and that land connection between the two continents of America was established in late Oligocene times. At four different times during the Oligocene and Pliocene periods the land sank below sea level, except, perhaps, for the higher peaks.

" In late Pleistocene times it was elevated to several hundred feet above its present level, then it sank to a depth of 6 to 30 feet below where it now stands. Very fresh-looking old raised sea beaches and other evidence indicate that this last upward movement began perhaps within the last 1,000 years.

" The geological instability of the land, particularly the last uprise, leads to the question as to whether the canal is in danger from emergence. If it were a rapid uplift, there would be some danger, but it seems to have been much lower than 0.03 of a foot (1 centimetre) a year, or 3 feet (1 metre) in 100 years. Dredging could, of course, take care of this, with very little additional expense above the ordinary dredging necessary for the annual upkeep of the canal. Then, too, there is always the chance that this motion will stop or be reversed into a sinking movement. In conclusion, then, it is quite certain that the canal is not in any appreciable danger from the geological instability of the Isthmium land." (See " Outline of Canal Zone Geology," by Donald F. Macdonald, *Trans. International Engineering Congress*, 1915, " The Panama Canal," pp. 76, 77.)

The alluvial plains of the Ganges River from the area in Bihar, where the disastrous earthquake of the 17th January, 1934, occurred, to the deltaic region of Bengal, requires notice. The Ganges has been spanned by one of the most important and costly railway bridges (for view see Frontispiece), and the river now threatens to change its course and pass south of the bridge. It is one of those cases which, had the geological history of the region been available to Sir Edward Gales, might have led to the construction of the bridge on dry land, and the river passed through it, subsequently, under control. Briefly, the history of this region is as follows: sea—the Bay of Bengal—covered the delta and extended into Sylhet and the Khasi Hills in the Cretaceous period, and persisted, even extended northward during the Lower Tertiary until Miocene times. Towards the close of this epoch, the Himalayas, the Assam range and the Yomas of Burma were being formed, and by Pleistocene times the Bengal sea had retreated southwards. The Ganges and Brahmaputra ultimately, but separately, discharged into it—the former due southwards, after rounding the Rajmahal Hills, and the latter, by a circuitous course by way of Mymensingh, after rounding the Garo Hills. Although the alluvium under Calcutta is over 480 feet thick it contains no marine fossils, and appears to be deltaic sediment throughout, and consequently indicates deposition and subsidence in delicate unison. Reckoned at 1 foot a century,

it shows that there cannot have been any sea in the Calcutta area for at least the past 5,000 years.

From historical evidence we know that less than 600 years ago the Ganges, as the Bhagirathi, flowed due south from below Rajmahal to the position of Calcutta, and thus to the sea. Since then this river has frequently left its previous main channel below Rajmahal, and each new river has taken a course east of the last, and so the river now discharges on a south-east course into the eastern end of the delta. The River Teesta about 150 years ago flowed due south from Darjeeling as a tributary of the Ganges, but since then it also followed a south-easterly course and discharged into the Brahmaputra. Until 100 years ago the main Brahmaputra deflected south-east into Mymensingh, as the old channel still shows, but it suddenly continued south, after passing west of the Garo Hills, and, as the Jamuna, discharges into the Padma from west of the Madhupur Jungle and Dacca. It was joined by the Ganges shortly after, and the confluence of these rivers has been subject to change since. The behaviour of these rivers indicates a narrow belt of special subsidence along a line north-north-west from roughly the confluence of the Ganges and Brahmaputra (Jamuna) Rivers. We already knew that the Ganges delta was a tract undergoing slow subsidence and that the Assam plateau was gradually rising. And geologically it has long been known that the bedded rocks of the Rajmahal Hills and the Raniganj coalfield dip eastwards under the alluvium, and would be at very great depths below the Brahmaputra. Recently Gondwana rocks have been found in the Garo Hills at the Brahmaputra, and the case now seems complete for assuming the presence of a strong line of faulting whereby sinking continues to the west of the fault line. It is this movement which affects the seaward gradient and course of the Ganges and is responsible for some earthquakes.

FOLDING.—In these days it is almost unnecessary to say that the massive sandstones and other laminated beds which are so often seen arched in huge flexures were once nearly flat as when originally deposited as sediment. The curious rippling due to water movement is often seen on the surfaces of such beds, and in many cases fossils are found in them to prove their marine origin. This bending and buckling indicates compressive stresses and shows that shortening of the crust has been effected, but the degree of folding and the condition of the material reveals something of the intensity of the pressures involved.

Also, it is found that the folding, although close along one belt, appears to pass gradually into almost unaffected strata when traced at right angles away from the zone of intense squeeze. Mention

has already been made of overfolded strata, and the development of thrust planes but these evidences of mechanical dislocation generally relate to strata subjected to less severe pressures than those which acted on some ancient rocks or newer mountain regions. The evidence of the closely-folded banded quartzite-hematite rocks shown in Photograph V reveals that this material must have been almost in a plastic condition, to have suffered so much contortion without fracturing. In some gneissic rocks the intensity of squeeze and the plasticity of the material appears to have been even greater than that depicted in Photograph V. While these examples refer to specimens and exposures of small extent, complicated folded structure may be studied on a great scale in the Alps, in the Himalaya, and other mountain areas. Not only has there been simple overfolding to the extent of several miles, but the same strata, in an attenuated condition due to squeeze and thrust, may overlie itself in long overfolds (*decken* or *nappe* structure) two or more times. It is therefore not surprising to read that the folded strata now occupying a width of, say, 100 miles, if resolved, would be two or three times wider.

There are many geologists who are inclined to the view that the crustal shortening in mountain regions, *e.g.* the Alps, is nearer 1,000 kilometres than 100 kilometres. Yet it is admitted that squeeze has occurred whereby the strata have become elongated and that thrust planes are present which indicate over-riding for several miles. Argand (*Eclogæ Geol. Helvet.*, 1916, p. 178) has likened the movement of the strata in parts of the Alps to the squeezing of paste from a tube, and we ourselves can readily call to mind the effect of rolling white hot ingots of steel to plates and bars whose length and breadth are out of all proportion to that of the ingot even when the thickness is barely reduced to a fourth. An ingot 2′×2′×6′ would yield a plate 12′×4′×6″, or a bar 24′×2′×6″ by rolling. In the case of the plate, there is a 100 per cent. increase in length and width, and in the bar the length becomes four times the original length. Such data have been collected in the study of the Alps and fully account for the complicated character of the *Decken*, and probably give some clue to the larger sweep which many mountain ranges take and which are explained as due to resistant "horsts" or forelands of crystalline masses.

In intensely-folded rocks, it is not unusual to find the beds thicker in the arches (anticlines) and troughs (synclines), and thinner in the limbs of the folds. Further, the rocks in the outer parts of the anticlinal and synclinal folds are frequently broken, as though as a result of the tension in bending. The rocks in the inner parts of the arch and trough of the folds are either crushed or tightly compressed. In the limbs of the folds, on the other hand, shear forces have developed

and caused the mineral grains of the rock to be pushed or thrust over each other. Some of the finest examples of elongation of plastic strata under squeeze occurs in occurrences of massive salt. H. G. Busk ("Earth Flexures," 1929, pp. 87–91) shows an excellent section through the Masjid-i-Sulaiman oilfield, Persia, where a plastic series (Fars) of clays and gypsum emerging from an anticlinal have become overfolded and recumbent, and thus overflow the adjoining syncline for two miles. So great has been the extrusion of the Fars beds that the whole series is quite thin under the opposite side of the anticline. Here is a typical example of *decken* structure, and a case where the lower side of the extruded Fars clays and gypsum are apparently overthrust on the younger rocks of the syncline. Busk refers to the extrusion of the plastic beds as " gamma structure " due entirely to static pressure plastic material. The east-west scarp of the Punjab Salt Range is disturbed at each end—towards the Indus and the Jhelum—as though from pressure by the mountains of Baluchistan and the Himalaya. The basal beds—the salt marls of Khewra—underlie Cambrian strata and thought by the author to occupy a normal position. The opinion more commonly held is that these plastic beds are of Eocene age and that the overlying strata have been pushed over them almost horizontally for over 20 miles from the north.

Folded rocks are generally well exposed in true mountain ranges; and in these regions it is usual to find the valleys which are parallel to the range carved along anticlinal (arch) flexures, whereas the ridges and line of highest peaks overlie synclinal (trough) folds, the explanation being that the rock *on* the arch was broken and easily eroded, while the rock *in* the trough was tightly packed and therefore more resistant.

It is known that a fold, on being traced along its axis, often changes in character. It is sometimes found to pass into a fault, or, possibly, to die out gradually. Similarly, faults have been found to die out without any evidence of folding. An interesting example of the change in the nature of a fold which very materially affects the working of a bed of bauxite occurs in the Departement de Var in France in a tract eastwards from S. Christophe, north of Brignolles to Parguette north of Le Luc (see Fig. 9). It will be noticed how the fault passes into an anticlinal fold which opens out gradually, while the syncline becomes tightly folded. These structural characters, together with the surface topography, have largely affected the cost of mining in the various localities mentioned. The total quantity of bauxite at Parguette is small.

These considerations are of general interest, but the engineer will see in the shattered jointed condition of some hard rocks, now only

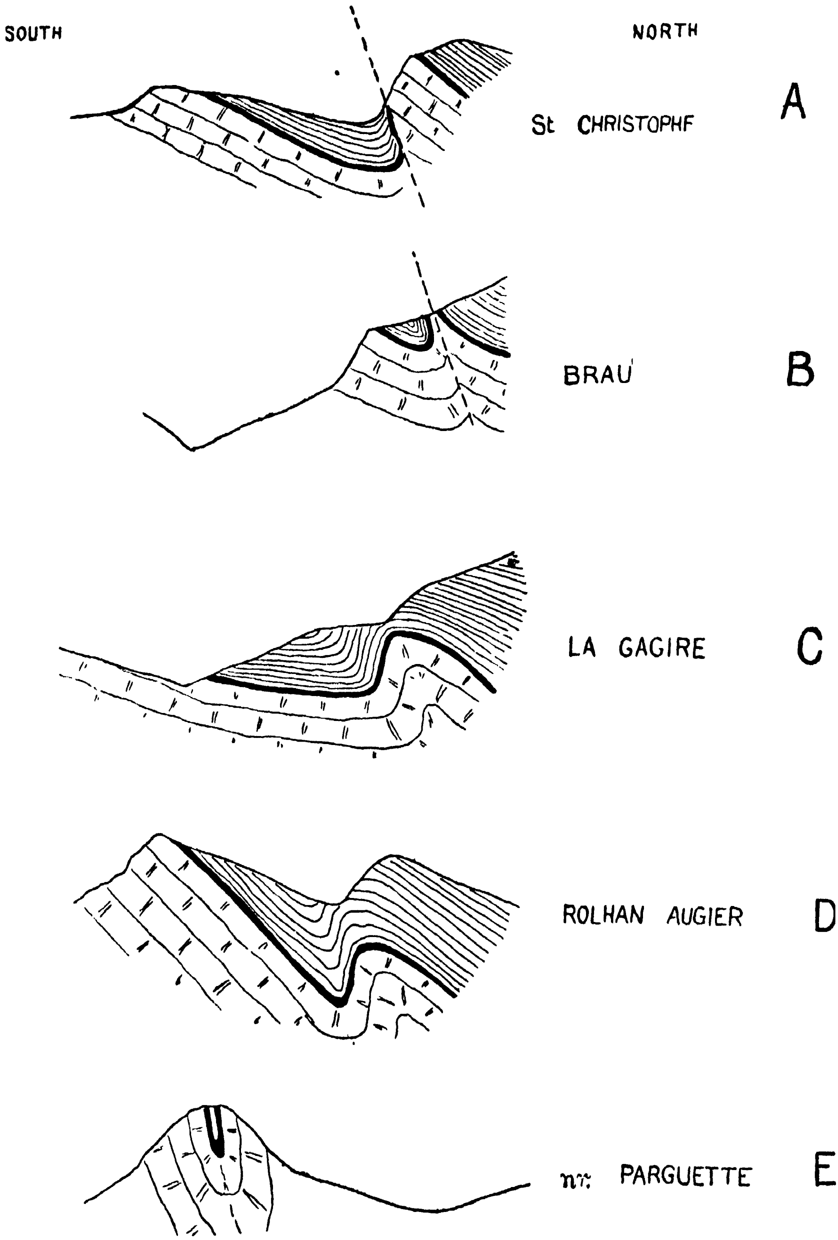


FIG. 9.
Relation of folds to faults.

N.B.—It will be noticed that the fault passes into an anticlinal fold when followed from A to E. Notice how the open synclinal becomes tightly folded in the same direction.

suitable for road metal or aggregate for concrete, conditions of compression insufficient to induce plasticity, and thus save the rock from crushing. In the intensely plicated gneisses he will recognise forces involving so high a temperature and pressure that "flow" has occurred without crush, and the material can be quarried in large blocks as excellent building stone. The petrologist will also point out to him that the microscopic texture of these "plastically deformed" rocks is different, and the material is crystalline and free of strain. It is a well-known fact that under severe conditions of pressure and temperature the minerals tend to crystallise in denser forms so as to occupy less volume. Dr. L. L. Fermor drew attention to this point several years ago in a paper entitled "Garnet as a Geological Barometer," because garnets are minerals which characterise zones of great pressure. Mr. R. D. Oldham accepts this as an explanation for some of the deeper layers of the earth's shell being more dense, although not necessarily of a different composition to a layer above. It is also true that a coarsely crystalline rock like *gabbro* will have a higher melting point than the crystalline material *dolerite*, and this in turn is less fusible than finely crystalline (anamesite) *basalt*, which also melts less readily than *tachylite*, and yet all these may give idential chemical analyses. It is an aspect which is possibly the secret of the true effects of the earth's contraction due primarily to loss of heat. It is a fact which has been slowly revealed by careful studies of the materials which are formed by different degrees of compression during periods of mountain building, *i.e.* by the folding, plication, and "flow" effects produced in the strata involved.

Before closing this section, mention must be made of the behaviour of various bedded rocks when subjected to bending and folding under conditions of great compression or squeeze. If a layer 376 feet long and 25 feet thick is placed on another of similar dimensions so that no relative movement can occur in their plane of contact, the sheet can be folded as shown in Fig. 10. Now, assuming the volume remains unchanged both in the arch and the trough, then the outer line of the arch (and the trough) will be 63 feet longer than the neutral line and the inner line of the trough (and the arch) will be 94 feet less than that of the neutral line. There will thus be an overall shortening of 31 feet (in 376 feet) or a little more than 8 per cent. on the curves of the layers —folding evidently produces bagginess. Now in actual experience great pressures are exerted and nearly all the rocks, especially the sedimentary rocks, are compressible. Suppose that in the layers considered the thickness of the top layer is squeezed down to 20 feet and no extension is possible perpendicular to the plane of the paper (Fig. 10), the length may increase to 470 feet, *i.e.* 25 per cent., if no

volume change occurs, or it may be less, and even zero, if the density of the material increases 25 per cent. Both these aspects require consideration in measurements of crustal shortening. The measurements of the strata involved in the *nappes* (*decken* structure) in Alps has led to the belief that the shortening may be as much as 200 kilometres (Albert Heim, *Geologie der Schweiz*, Vol. II, p. 50, 1921), and similar measurements are given for the Appalachians (A. Keith: *Bull. Geol. Soc. Amer.*, Vol. XXXIV, p. 335, 1923) and other mountain belts. Jeffreys considers that internal loss of heat of 500° C. to a depth of 400 kilometres can cause a 5 per cent. volume contraction of the outer shell. This would be 20 kilometres on the earth's radius or 130 kilometres on the circumference, and involve probably 200 kilometres, which would mean 5×10^{16} square centimetres. He states ("The Earth," 2nd Edn., 1929, p. 282) that the contractions of the various mountain belts and their extent are accommodated in about half this extent of the earth's surface shrinkage, so that ample provision is made for the contraction. It is understood that in resolving the folds of mountain sections, due allowance is made for elongation by squeezing and the total contraction not exaggerated.

A problem which is forever new is that presented by the adjustment of the crust of the earth as contraction occurs due to loss of heat from the earth's interior. The evidence in every mountain region shows that all kinds of rocks—limestones, quartzites, granites, etc.—become buckled and plicated as though in a plasitc condition when under great pressure. The question, however, is whether this folding and overfolding due to orogenic movements fully accounts for the adjustment necessary, or whether part of the crustal shortening may be due to the crustal rocks being forced downward into the sub-crustal zone. That uplift of the crust occurs is evident in the mountain ranges that we see, but the extent of the crustal shortening which can be estimated by unravelling the folds is liable to considerable error if no allowance is made for elongation due to squeeze. Dr. Bucher has calculated that a contraction of one mile in the radius of the earth for a crust 60 miles thick means a void of over 190 million cubic miles in the sub-crustal zone. He further computes a reduction of surface, to meet the contraction, of two great circles 25,000 miles long each by a width of 2 miles. This for a crust 60 miles thick means the elimination of only 6 million cubic miles—a mere fraction of the calculated void. However, the void is really filled by the crust itself while the 6 million cubic miles has to be adjusted. It is of this 6 million cubic miles that we must account either from the uplift of mountains or partly by a downward elimination.

Jeffreys, however, discloses that even with the estimate of shorten-

ing for the Alps given by Heim, which involves a ratio of 3 to 1, there appears to be too great a contraction calculated. He supposes a section of the crust as follows: 1 kilometre of sediments of density 2.4; 10 kilometres of granite of density 2.6; 20 kilometres of tachylite of density 2.9, and the whole resting on dunite of density 3.3. If the upper layers are compressed to double their thickness, *i.e.* giving an increase of 31 kilometres which could be balanced by 26.2 kilometres of dunite. This would leave an elevation of 4.8 kilometres, which is more than the height of Mont Blanc, and caused only by a shortening of 2 to 1. He adds that erosion in mountains is usually restricted to the sides and slopes, and not to tops and peaks, and involves the upper

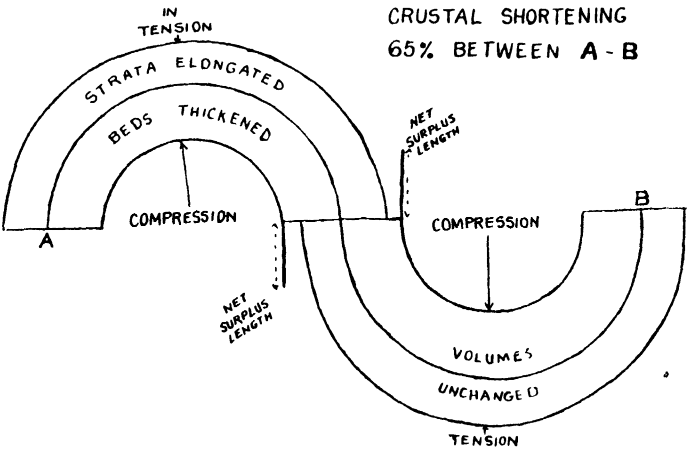


FIG. 10.
Crustal shortening.

lighter rocks—1 kilometre of these being equal to 0.73 kilometres of dunite. It follows that an erosion of 1 kilometre thickness actually causes a loss of height of only 0.27 kilometres as a whole, and that the mountain peaks, if denuded less than the valleys, will be increased and not lowered. From these considerations he shows that the crustal shortening in the Alps and Rockies is about 1.66 to 1, and 2.2 to 1 for the Himalaya—very considerably less than the measurements of the folds suggest. This mode of elucidating geological problems by an appeal to mathematics is becoming fashionable, as it certainly gives a definite answer to questions which have been argued over and over again without so clear an explanation.

FAULTS.—Geologically speaking, a fault is the plane of fracture along which rocks have suffered dislocation. The sections across various types, seen in Figs. 9, 10 and 11, illustrate the relative movements which normally occur. Such fracture planes are believed to be absent in the deeper layers of the earth's crust, where the tempera-

tures and pressures are so great that any adjustments can readily be made by plastic deformation, as already explained above. Thus fissuring, fracture planes and shear zones, are the evidences of rock adjustment to strain in the outer crust—the upper or granite layer—where the strata are relatively brittle and have freedom for movement greater than in the deeper layers.

In general, faulting appears to be due to vertical shearing forces resulting from a tendency for the crust to sag, which is thought to be the consequence of internal contraction from cooling. Whatever may be the true cause, the chief result is shearing and buckling (folding) of the strata (Fig. 9) in the upper crust. When the subsidence effect becomes restricted to a narrow belt, blocks of the crust are let down by parallel faults, and great surface troughs or rift valleys result, such as those of East Africa and the Red Sea and the Jordan valley. In other cases large blocks of land sink beneath the sea, as occurred in early Tertiary times in the Arabian Sea, when the westward land connection between India and Africa subsided. Even after the most disastrously violent earthquakes due to faulting, the surface displacements seen are very rarely greater than 10 feet either vertically or laterally, and yet there are well-known fault lines, trending for miles, across which the vertical dislocation may be 10,000 feet.

The main boundary fault of the Raniganj coalfield and of others in the Damodar valley are of this order. Such movements can only have taken place in small, unnoticeable amounts—less than an inch a year—over a very long time—120,000 years at the above rate for the Raniganj fault, but it is far more than this.

The maximum depth to the supposed focus of any great earthquake is probably in the basalt layer, about 24 miles (see page 155), and faults can hardly extend to any such depth. Their planes act as channels for the movement of highly heated waters carrying mineral matter in solution, which on rising and cooling deposit these substances, seal up the fault plane, and thus establish a mineral vein. Similarly, in sub-surface regions the movement of percolating waters may choke fault fissures with clay and hold up relatively dangerous volumes of water in the strata on one other side of the fault. After the Bihar earthquake of January, 1934, which was felt quite strongly in the coalfields of the Damodar valley, many fault planes were evidently re-opened in the coal-bearing strata. In the Jharia coalfield in particular it was noticed that the workings of mines on the upthrow side of important faults were drained of their water, and that mines to the downthrow of similar faults or which were traversed by faults connected with the bed of the river were seriously affected—some workings were actually drowned out—by the large influx of water. In a

few cases the rate of pumping has still to be kept at a greater amount than was necessary before the earthquake. To what extent this state of affairs is due to regular feeders, diverted along faults to the mines, or to the discharge of standing underground water, is not yet known. It is unnecessary to say that it is nothing short of madness or absolute ignorance to neglect the presence of apparently old faults when a

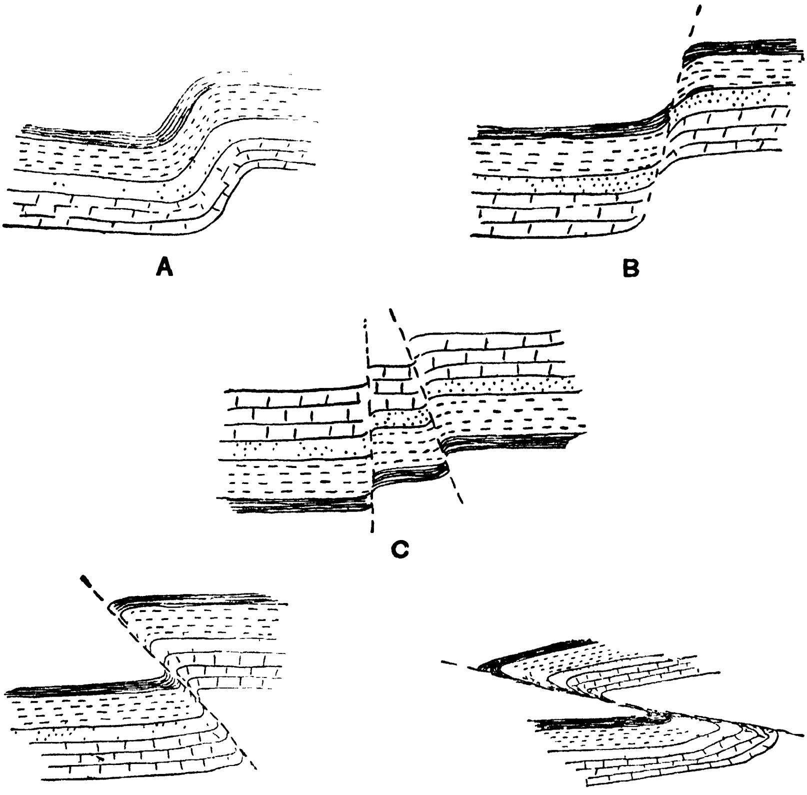


FIG. 11.
Types of faults.

A—is a monoclinal fold in section.
B—a normal fault; C step faults.
D—a reverse fault and E an over-thrust.

tunnel or bridge or any important engineering work is under consideration, for some of the faults of the Jharia coalfield are traceable into the gneissic areas beyond as reefs of quartz rock.

In regions where great compressive forces produce mountain uplifts and squeeze the strata into folds, there is always a fall over of the folds in one or other direction at right angles to the axis of the range. This is invariably accompanied by shear faulting whereby the successive beds or folds are thrust over or under the next below or above, but it is difficult to ascertain with certainty whether over-

thrusting or under-thrusting has occurred. Generally, seeing there is less weight on the upper beds, the tendency must be for over-riding (over-thrust), but in the case of what were more deeply buried strata, under-thrusting can often occur. These are, however, matters of academic interest in most cases for purposes of estimating the direction of the forces and in calculating the compression (contraction) involved, in a horizontal plane, of the earth's crust. It is unwise to erect large engineering structures in regions of active thrust movement, but these are few or restricted to the actual thrust planes. Professor Charles Lapworth showed the important effects produced by thrust faulting in the southern upland of Scotland, and this type of structure is very well developed along the south side of the Himalaya. In fact the structure across the Himalaya from south to north suggests that the whole range is pushing south. The reversed faults or thrust planes are generally followed by older and older strata—the younger dipping under the older due to overfolding—suggestive of a reverse order of their relative geological ages. Thus sandstones of Upper Tertiary age dip under coal measures of Upper Palæozoic age, and these in turn under quartzites and slates of Pre-Cambrian, and these, again, under gneisses and schists presumably of Archæan age. The degree of shearing may be gauged by the fact that the coal in the coal seams is in a condition of flakey powder and has a decided anthracite character —the volatile matter being reduced from 30 per cent. to 15 per cent., and even 7 per cent. in some exposures.

HEAT PRODUCED BY INTENSE CRUSHING.—Robert Mallet (see *Phil. Trans.*, 1873, p. 187) found that certain quartzitic rocks and slates, although capable of withstanding a pressure of nearly 6 tons (12,000 lbs.) per square inch before their elastic limits were passed, suffered a linear compression, at this pressure, of 0.13248 per unit length for the quartzitic rock and 0.04464 for the slate.

Converting these values into foot-pounds on prisms of one square foot cross-section and 100 feet length, and dividing by Joule's equivalent, he obtained a theoretic development of 295.2 British thermal units of heat in the quartzitic rock and 100.8 British thermal units in the slate. These calculations indicated that the heat developed in the quartzitic rock would be nearly three times that which could be developed in the slate.*

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* MEASURE OF HEAT.

BRITISH THERMAL UNIT = quantity of heat required to raise one pound of water one degree Fahr. (exactly, from 39.1° to 40.1°).

MECHANICAL EQUIVALENT OF HEAT.—Where heat is converted into mechanical energy, 778 foot-pounds is produced for each British thermal unit expended. (This used to be taken as 772 foot-pounds, but this quantity has been proved to be too small).

CALORIE = the amount of heat required to raise 1 kilogramme of water 1°C.

1 calorie = 4,200 joules = 42×10 ergs.

Pursuing his investigations further, he experimented with sixteen varieties of rock, and tabulated his results in an elaborate table, from which the following columns have been extracted.

The list of rocks (6 specimens of each) actually crushed were:

(1) Oolitic limestone from Caen and Normandy;
(2) Oolitic limestone—Portland stone;
(3) Dolomitic limestone—Magnesium limestone of Yorkshire;
(4) Sandstone from Bradford, Yorkshire;
(5) Sandstone (fine) from Ayre Hill, Yorkshire;
(6) Sandstone (coarse), millstone grit, Bramley Fall;
(7) Limestone, Devon marble of Carboniferous Age;
(8) Slate from Conway of Cambrian Age;
(9) Slate from Bangor of Cambrian Age;
(10) Basalt from Rowley Regis in Staffordshire;
(11) Granite (red) from Dartmoor, Devon;
(12) Granite (grey) from Guernsey;
(13) Syenite (hornblende) from Mount Sorrel, Leicestershire;
(14) Granite (blue) from Aberdeen;
(15) Granite (grey) from Aberdeen; and
(16) Porphyry from Furnace Quarry, Inverary, Scotland.

The pressures utilised and the theoretical estimates of temperature per cubic foot of rock and the B.T.U.s per lb. (avoirdupois) of crushed material, etc., are shown on page 149.

From these figures it is evident that when rocks are subjected to very great pressure an enormous development of heat is possible. Daubree has shown (see *Geol. Experimentale*, p. 448) that mutual friction between the component particles of a firm brick-clay may increase the temperature of the clay mass from 18° C. (65° F.) to 40° C. (104° F.).

In actual practice, seams of coal, which are known to have been subjected to the superincumbent weight of 8,000 to 10,000 feet of strata, have been found to have suffered partial conversion into

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MEASURE OF FORCE AND WORK.

POUNDAL = The force which, acting on a mass of 1 pound, gives it a velocity of 1 foot per second.

DYNE = The force acting on 1 gramme for 1 second which gives it a velocity of 1 centimetre per second.

ERG = The work done by a force of 1 dyne through a distance of 1 centimetre.

GRAVITY.

Force of gravity acting for 1 second on a mass gives it a downward velocity of 32.17 feet per second.

POWER.

Horse power, adopted as the unit of power = 33,000-lbs. raised 1 foot high per minute. The actual tractive force of a horse, working 8 hours a day on a good road, walking at $2\frac{1}{2}$ miles an hour, is 150-lbs. A horse can exert a pull of 400-lbs.

A man, working 8 hours a day, can lift a weight of 40-lbs. 25 ft. per minute = 1,000-lbs. raised 1 ft. per minute. But in rowing a boat, when he exerts his force to the greatest efficiency, he does the equivalent of raising 3,200-lbs 1 foot per minute, or nearly $\frac{1}{10}$ horse power. For a few seconds he can exert a very much greater power.

anthracite. In other cases, however, certain sedimentary rocks which are estimated to have been buried under 50,000 feet of overlying strata, although very hard, still retain their distinctive elastic characters, and show no sign of conversion into schists or similar metamorphic rocks.

It seems, therefore, that in certain cases a considerable absorption of heat by the rocks themselves must take place. In proof of this it may be mentioned that certain clay slates, clays, and coal, when finely powdered and mixed with water, evolve heat.

From such theoretical considerations and facts as have been outlined above it appears logical to conclude that the presence of water in rocks exposed to intense pressures will promote the evolution of heat. The development of heat would certainly produce re-crystallization of the mineral constituents with a consequent reduction in the volume of the rock. This would release the mass of the rock from much of the strain previously induced in it. Indeed, it is the opinion of many geologists that some such action causes the metamorphism of clay slates into schists and gneisses, limestones into marbles and calc-gneisses, etc. Such an idea is conveyed in the sections shown in Figs. 56 and 57, where gneissic rocks are shown in positions where the tectonic pressures are thought to be greatest.

Sir James Hall (see *Trans. Roy. Soc., Edin.*, Vol. VI, 1805, p. 101) found that if powdered chalk was hermetically sealed in a gun-barrel and exposed to the temperature of melting silver, it was melted and partially crystallised, but still retained its carbonic acid; when, however, the chalk was similarly exposed, with the addition of a little water, it was transformed without fusion into marble. However, the investigations conducted by A. Gautier (*Compt. Rend.*, Vol. CXXXI, 1900, p. 647; Vol. CXXXII, 1901, pp. 58 and 189; Vol. CXXXVI, 1903, p. 16) showed that heating a rock powder to redness with water resulted in the production of gases closely resembling those from volcanoes, *i.e.* largely carbon dioxide and hydrogen, if the materials are in vacuo. In fact, he thought that volcanic phenomena are due to fissuring and subsidence whereby the crystalline rocks are lowered into the heated sub-crustal zone of the earth's crust. He showed that a cubic kilometer of granite would yield about 25 million tons of water and over 5,000 million cubic metres of hydrogen (at normal temperature and pressure). This amount of hydrogen burning would yield further water and the total quantity of water thus evolved, nearly 30 million tons, is as much as flows in the Seine at Paris in 12 hours. According to F. W. Clarke (*Data of Geochemistry*, 1920, pp. 283–84):

"One gram of hydrogen, burning to form water, liberates a

	Sp. Gr.	Wt. per cubit ft. lbs	Pressure at 1st fracture lbs. per sq in	Pressure to crush lbs.	Pressure to entirely crush.	Work done foot lbs.	Sp. ht. $H_2O = 100$	B.T.U. (per lb. avoir).	Temp. in 1 cub. ft. of rock.
1	2.337	145.829	1620.26	2410.2	4966.	439.92	0.284	2.27	8.004
2	2.462	153.629	3138.00	5848.4	13216.5	1259.13	0.265	5.5	20.98
3	2.571	160.430	3699.00	7409.0	16333.3	1483.98	0.245	6.4	26.28
4	2.478	154.627	10970.60	14011.0	29783.3	2807.67	0.215	19.3	86.13
5	2.408	150.259	sudden collapse	7301.0	15966.6	1487.69	0.223	11.1	47.79
6	2.506	156.374	"	5049.0	11500.0	1295.32	0.238	7.8	32.84
7	2.717	169.540	11708.30	15684.0	34938.0	3416.36	0.203	23.2	114.68
8	2.733	170.539	9768.30	12543.0	27704.3	2051.87	0.218	28.9	132.85
9	2.859	178.402	15510.00	18439.0	41590.0	3438.34	0.201	28.9	144.29
10	2.827	176.405	24039.30	29125.0	63737.0	6465.43	0.204	44.6	213.23
11	2.652	165.485	15191.33	19389.0	42965.0	4369.73	0.180	20.9	116.39
12	2.858	178.340	20903.33	30123.0	67715.0	6433.47	0.189	41.0	217.24
13	2.653	165.550	19976.33	26201.0	58988.0	5973.66	0.181	33.0	182.27
14	2.707	168.917	20125.66	22681.0	51985.0	4631.44	0.215	25.7	119.20
15	2.678	166.907	16868.00	22316.0	51123.0	5176.67	0.196	30.5	155.94
16	2.594	161.866	26149.00	30975.0	69786.0	7108.54	0.186	37.0	198.97

quantity of heat represented by 34,000 calories; that is it would raise the temperature of 34,000 grams of water from 0° to 1° C. This reaction alone, this combustion of hydrogen in air, evidently plays a very large part in the thermodynamics of volcanism."

Crystallisation from dry fusion is quite a different matter. In such cases the molten mass of any rock, whether shale, sandstone, basalt, or granite, if cooled quickly, results in the formation of glass; but if the fluid substance be allowed to cool slowly, more or less distinct crystallisation sets in, and a lithoid product is obtained. In this connection the following remarks extracted from *The Data of Geochemistry* (F. W. Clarke, 1920, p. 285 *et seq.*):

" We can measure the temperature at which lavas and their component minerals fuse, under ordinary conditions of pressure, but these melting points are modified by various agencies within the depths of the earth. . . . By pressure, which steadily increases as we descend into the earth, the melting points must be raised, but on the other hand the gases that we know to be present in the molten mass tend to lower them, and the latter tendency is probably the stronger. . . ."

" In the geological interpretation of the melting points there is one particularly dangerous source of error. We must not assume that the temperature at which a given oxide or silicate melts is the temperature at which a mineral of the same composition can crystallise from a magma. . . ."

" . . . All we can now say with certainty is that the temperature of an emerging lava must be above that at which it begins to solidify. That temperature is rarely, if ever, below 1,000 C., and the actual temperature not long before emission may be hundreds, perhaps a thousand, degrees higher. . . ."

" . . . The magma, before eruption, is something very different from the smoothly flowing stream of lava, for it is heavily charged with aqueous vapour and other gases, under great pressure, exactly as the soda water in an ordinary syphon bottle is loaded with carbon dioxide. When the pressure is released the gases escape with explosive force, carrying the liquid matter with them. . . ."

" . . . An igneous rock, so far as our data now go . . . becomes fluid at temperatures below the average melting point of its constituent minerals, and sometimes lower than the lowest among the latter. . . ."

" . . . When a fused rock, or mixture of similar character, solidifies, it can do so in either one of two ways. It may solidify as a unit, forming a glass, in which no individualisation of its constituents can be detected, or it may solidify as a mass of crystalline minerals, each one exhibiting its own pecularities. Between these extremes many intermediate conditions, due to partial crystallisation, are possible, ranging from glass . . . to a crystalline mass. . . ."

" . . . F. Guthrie (*Philos. Mag.*, 4th ser., Vol. XLIX, 1875, p. 20), to whom the expression " eutectic ' is due, was the first to point out the applicability of his researches to the study of igneous rocks. . . . J. J. H. Teall (*British Petrography*, 1888, pp. 395–419) was one of the

first to develop the subject, and he indicated a micropegmatite, with 62.05 per cent. of feldspar and 37.95 per cent. of quartz, as a possible eutectic mixture. . . ."

"... It is, however, a grave question whether in a strict sense eutectics of feldspar and quartz are possible. Quartz is capable of formation only below 800, and one modification of it only below 575. In the pegmatites of Maine, as described by E. S. Bastin (*Jour. Geology*, Vol. XVIII, 1910, p. 297), the quartz is often of the low-temperature variety, and crystallisation was further modified by the presence of gaseous or vaporous constituents in the magma. Fluid inclusions are also common in the quartz. . . ."

"... It is evident, from what has been said, that no universal concrete rule can be laid down to determine the order in which the different minerals will separate from a cooling magma. . . ."

"... Another process which surely plays some part, great or small, in the differentiation of magmas is the solution of foreign material. The molten lava, as it rises from the depths to the surface of the earth, is enclosed between walls of rock upon which it exerts a solvent action. . . ."

CHAPTER VIII

THE EARTH'S TREMORS

VOLCANOES.—The ancient tragedy of Herculaneum and Pompeii about A.D. 79 has been followed by similar volcanic eruptions in various parts of the world—the better known, perhaps, are the outbreaks in Iceland in 1783, Krakatoa in 1883, St. Pierre in 1902, Etna in 1913, etc. The Pacific Ocean is girdled with volcanoes and others lie along definite structural features or orographic axes. The word itself now conveys the sense of uncontrollable stupendous forces of an explosive type which are accompanied by clouds of steam and dust, scorching acid vapours, floods of hot fluid mud and a discharge of scoriaceous lavas. There are great variations in actual volcanic action, as the quiet welling up of fluid molten lava in the basaltic cauldrons of Kilauea in Hawai. The intermittent rushing discharges of steam and boiling water from the geysers of New Zealand and other places are thought by many to have volcanic relationships. The famous fluid bitumen of Pitch Lake, Trinidad, although hot and suggestive of volcanic action, is probably a by-product of such activity by the accident of association of bituminous strata in a volcanic region. The same explanation is not true for the curious mud volcanoes in the delta of the Mississippi, where chemical action is alone responsible. In the case of the extrusion and flow of salt from "plugs" in Persia, the cause is clearly that of pressure producing plasticity in a suitable material. Nevertheless, the various types of volcanic and pseudo-volcanic action mentioned generally have one factor in common—that is, they occur in areas of relatively recent folding, but this is not a rule. Hot springs are frequently associated with areas of faulting rather than folding, and volcanoes are themselves sometimes curiously isolated. There is not a single volcano throughout the length and breadth of the Himalayas or the Alps, although evidences of such are available in Persia and Burma in a more or less defunct form, and in Italy in an active condition.

In his book, "The Problem of Volcanism," 1914, J. P. Iddings says it is

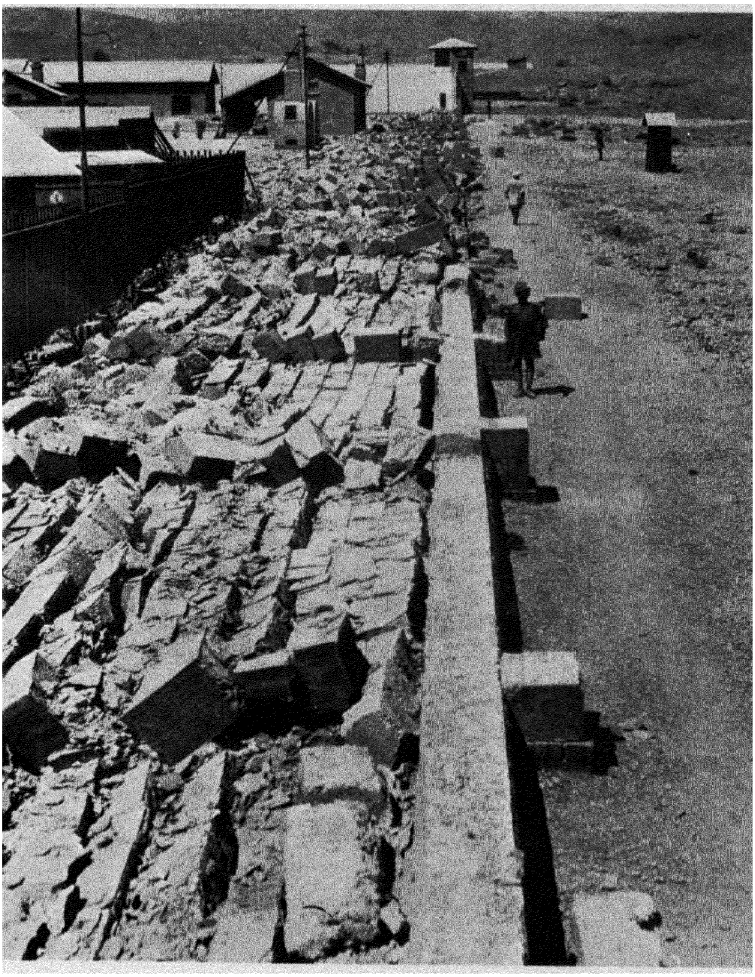


Photo by W. D. West.] [*D.G.S.I.*

A FALLEN WALL.

This wall of the Mach jail near Quetta, collapsed during the Baluchistan Earthquake of August 27, 1931. The undulations probably travelled at right angles to the wall. It has fallen away from the buttressed side.

[*To face page* 152.

"a subject as old as the hills; a process that must have preceded them; a question that carries our thoughts back to a time when the earth may have been a nebula, 'without form and void,' a speculation that has excited the liveliest imagination of men in all ages, and has taxed the intelligence of the ablest geologists; such is the problem of volcanism, which yet remains, as Dutton has said, first of the greater problems of physical geology."

What is the potential cause of volcanic action? Frankly, we do not know, although various hypotheses have been advanced in explanation of the phenomena. One fact is significant. This is, that active volcanoes are situated in close proximity to the sea—either on bordering mountain chains or along a string of islands. There are, as already stated, no volcanoes in the Himalayas, while the Pacific is girdled by active volcanoes. The obvious inference is that water must penetrate to the highly heated zones of the earth's crust, and by conversion into a gaseous condition, somehow play an essential part in volcanic action. In the early days of radioactivity C. E. Dutton advanced the view that this might be the cause of some volcanoes—due to the heat evolved, locally, at small depth, from enrichments of radioactive elements. His views had the support of Professor J. Joly from the estimation of abnormal amounts (12.3×10^{-12} grams of radium per gram of rock) of radioactive elements in the lavas of Vesuvius. There is no reason against such a cause for some volcanic activity, but few geologists would advance this explanation as the general cause of volcanic action to-day.

Dr. F. W. Clarke ("Data of Geo-Chemistry," 1920, p. 209) has stated that

"1 cubic kilometre of granite can yield from 25 to 30 millions of tons of water, which at 1,100°, would form 160,000,000,000 cubic metres of steam. In addition to this enormous volume of vapour, 28,000,000,000 cubic metres of other gases would be emitted. Suppose, now, that by fissuring and subsidence in the lithosphere such a mass of rock were carried down to a depth of 25,000 to 30,000 metres. It would then be in the heated regions, and the evolution of vapours would occur. . . ."

and on page 256 he adds that

"F. Fouque, observing one of the many parasite cones on Etna, estimated that in one hundred days it discharged vapour equivalent to 2,100,000 cubic metres of water, or 462,000,000 imperial gallons. This great quantity is only a small fraction of what the entire volcano must have annually emitted. . . ."

It is beyond the purpose of this book to deal with so speculative a subject as the cause of volcanic action. Sufficient is known regarding the general location of volcanoes which have been active during the historical period to enable engineers to recognise and, if necessary,

avoid their vicinity in erecting important structures. The extinct volcanoes of the Tertiary period are equally well known, and a great deal of information is available regarding the " dead " volcanoes of the earlier geological epochs. The subject of volcanoes in general has been dealt with by numerous writers ; but, for the student, there is an elaborate account in Sir Archibald Geikie's " Text Book of Geology " (Vol. I, Book III, Part I). A chart of the world, showing the areas of volcanic activity since tertiary times, with ocean " deeps " according to Sir John Murray, is appended to Iddings' book.

Sir Archibald Geikie draws attention to several cases of submarine volcanoes, and he states that although most terrestrial volcanoes are situated near the sea, " volcanic activity is displayed over a wider region of the ocean floor than over the surface of the land, and on a more gigantic scale."

With regard to terrestrial volcanoes, he recognises two distinct types of structure—(*a*) Volcanic cones and (*b*) Fissure eruptions—" according as the eruptions proceed from large central orifices or from fissures that reach up to the surface." Of the latter type, perhaps the most stupendous example occurs in the basaltic lava flows which cover parts of Oregon, Washington, California, Idaho, and Montana—an area greater than France and Great Britain combined. The basaltic lavas of the Deccan in India which overwhelmed Gondwanaland after the close of the Mesozoic period, although worn down, still cover 200,000 square miles of country, and in places have a thickness exceeding 4,000 feet. They are but a remnant of a vast outpouring of lava, chiefly from fissure eruptions. As regards volcanoes of the cone type, Sir Archibald Geikie distinguishes them as :

(1) Explosion craters, such as those of Lonar Lake in Hyderabad State (India), Coon Butte in Arizona (U.S.A.), etc., which are thought to be due to a sudden explosion of the Krakatoa type.

(2) Cones of non-volcanic materials produced by the discharge of steam and the fracture of the rocks at the mouth of the vent, as in the case of many cones in Central France.

(3) Cinder cones resulting from the ejection of dust and stones which have become mixed with the water from condensed steam to form tuff cones similar to those scattered over the plains of Utah.

(4) Mud cones which have formed by the consolidation of outpourings of mud, such as those near Minbu in Burma and in the area west of the lower Indus.

(5) Lava cones composed entirely of lava are rare, but are well exemplified by the flat cones of Mauna Loa in Hawaii and the gigantic dome of Chimborazo in Ecuador; and

(6) Cones of lava and tuff, the most abundant type, such as the peaks of Teneriffe and the craters of Vesuvius, Etna, etc.

It is a curious fact that the active volcanoes of the present day are in general not coincident with the centres of volcanic activity of past ages; they occupy new areas. There is perhaps some comfort in the thought that a city built on a "dead" volcano is, in most cases, immune from further volcanic activity. Unfortunately this does not mean that the site of an extinct volcano must necessarily be immune from all kinds of earth-movements. The volcanoes of Baluchistan and Eastern Persia have become extinct during comparatively recent times, yet these areas are subject to severe earthquakes. The crust of the earth appears to be subject to oscillating adjustments tending towards equilibrium, long after the active volcano has ceased. Remembering that the Deccan volcanic activity continued after the end of Cretaceous times and the Himalayan uplift began subsequently in late Eocene period it is impossible not to suspect a direct relationship between the two. The mountain ranges of Baluchistan and of the North-West Indian hinterland, the Himalayas, and the mountains of Burma have a very suggestive sweep with regard to the locus of the Deccan lavas. These ranges appear to form almost a semi-circle of earth-waves or ripples, as though the earth's crust had pushed towards the Deccan in an endeavour to fill the enormous cavity from which the basaltic lavas had been extruded.

EARTHQUAKES.—The majority of severe earthquakes appear to originate within the earth's crust about the base of the granite layer or at a less depth, *i.e.* rarely more than 7 or 8 miles down. They are believed to be due to a sudden shearing or slip of the rocks under accummulated strain by distortional stresses. The tremors of these relatively deep-seated earthquakes are recorded almost at all possible seismograph stations, and it is well established that the most violent volcanic eruption gives rise to a very feeble earthquake. During the present century two somewhat curious earthquakes have been produced, naturally and accidentally, to supply illustrations of great interest. The one, referred to as the Turkestan Earthquake of the 18th February, 1911, was finally traced to an enormous landslide in the Pamirs—a fall of over 500,000,000,000 tons of rock slipping 1,500 to 2,000 feet. The other was the result of the explosion in the Badische Analin und Sodafabik at Oppau in Bavaria on the 21st September, 1921, of 4,500 tons of the double salt ammonium nitrate

and ammonium sulphate. Both produced weak earthquakes, but the tremors of the former are believed to have been received in Canada, whereas the latter was not noticed beyond 300 miles. The great earthquakes of Mino Owari (1891), Assam (1897), Kangra (1905), California (1906), Kwanto (1923), Tajima (1925), Oku Tango (1927), Bihar (1934), among those fairly well known to us, were in each case disastrous to property and loss of lives. Earthquakes cannot be forecast to the month or year, although they may be known as likely in certain areas, but this is not of much value except to insurance companies or far-sighted engineers who must face the risk.

Most earthquakes occur suddenly. There is seldom any warning. On some occasions a tilt of the ground (Japan) or slight preliminary tremors have been noted. More rarely deep rumbling sounds have been heard. These subtle signals, however, are rarely any guide to the intensity of the earthquake that quickly follows. In a severe earthquake it is difficult to stand up within a few seconds after the earthquake has begun. Records of the great Assam Earthquake (1897) show that deep rumbling sounds were audible two seconds before shock, which reached its maximum movement almost at once. The ground swayed backwards and forwards, producing a sensation of sea-sickness. The surface vibrated visibly, as though made of jelly. Low banks of earth or piles of road metal were shaken flat. Cracks appeared and closed with the wave motion of the ground. Buildings shook and plaster began to fall at once, and a few moments after the walls gave way and the bent and broken roofs subsided in a heap. The shock appeared to have lasted about a minute, but most of the damage had been done in the first twenty seconds. (See *The Statesman*, 24th August, 1930.) Experiences and observations of a similar nature can be quoted from accounts of other eye-witnesses of earthquakes in all parts of the world. The violence of the forces operating are evident from the ruin they cause by actually shaking the earth's crust. In many cases it is evident that the damage to buildings would have been less if they had been better and more suitably built, as will be shown later. The question of design or of materials will not, however, ensure safety in the epicentral tract of the more severe earthquakes. The forces are too great and beyond human ability to control or deflect.

The section of the earth shown in Fig. 14 includes our ideas of the vibrations and waves which are set going by an earthquake and the manner of their passage through the earth or along its surface. Putting aside all questions of the possibility of complication by reflection or refraction of the seismic waves at the surfaces of the several layers of the earth's shell, and particularly those of marked discontinuity at

60 kilometres and 2,900 kilometres, it is only necessary to consider three main types of waves. These are very simply discussed in a valuable paper—" The Machinery of the Earth "—which Professor J. W. Gregory delivered as the 17th Thomas Hawksley Lecture (*Min. Proc. Inst. Mech. Eng.*, 17th November, 1930), from which Fig. 13 is copied.

The fastest vibrations and those which arrive first at a seismograph situated outside the epicentral tract are the so-called *primary*. or P (push) waves. They are short waves of a compressional (to and fro) or longitudinal type, and are transmitted through fluids, solids, and more rapidly in denser solid media. Their rate of travel through the earth's shell is given below with those of the next rapid *secondary* or S (shake) waves. These are distortional waves with vibrations transverse to the direction of propagation, and can only be transmitted by solid (elastic) media, and not by fluids. Their amplitudes are small compared with the third kind of waves which only travel along the earth's surface. These ground or Raleigh waves travel like the waves of the sea, with a rotary movement in the vertical plane of the direction of propagation. They are slower than the S waves, have far longer wavelengths and amplitudes than the others, and are believed to be produced by the P and S waves. They are called L (long) waves on seismograms and it is through them that the greatest surface damage is usually done. They are evidently not felt in deep mines.

RATE OF TRAVEL OF P AND S WAVES IN KILOMETRES PER SECOND.

Media.	Depth	P	S
Granite	10 kilometres	5.4 to 5.6	3.3
Basalt..	below 10 km.	6.2 to 6.3	3.7
Dunite	below 40 km.	7.8	4.35
Inner Shell	below 1,200 km. to 2,900 km.	Up to 13.0	Up to 7.2
Core	below 2,900 km.	8.5	—

(After B. Gutenberg : *Lehrbuch der Geophysik*, 1929.)

In the case of the Dhubri Earthquake of the 3rd July, 1930, E. R. Gee (*Mem. Geol. Surv. India*, LXV, 85, 1934) has given the following rates of travel in arcual distances :

Place (Dhubri as centre).	Distance (arc).	Rate in km. per sec.		
		P	S	L
Alipore	7.54°	7.2	?	4.0
Dehra Dun	14.63°	7.3	4.4	3.4
Colaba	21.5°	8.4	4.6	3.6
Colombo	24.46°	9.1	5.0	3.5

The rumbling sound which is frequently heard at the time of earthquakes, and which the author has himself heard in the Garo Hills during an earthquake, appears to be caused by the oscillations of the ground—the surface functioning as a telephone diaphragm. If the surface waves, L waves, travel at 2 miles a second, it is difficult to believe that the sounds are heard before the tremors arrive. My observation was that the sounds I heard were evident during the earthquake above referred to, but others have heard the sound earlier. Also, there are several records to the effect that the ground oscillations were clearly visible (" like wind over corn ") and that the waves were 1 to 3 feet high and 200 feet long (like true water waves). From these accounts, which relate to areas of great disturbance, it would appear that the surface waves must change as they travel outwards, or that there are two types of surface waves—larger and slower waves nearer the epicentre and the so-called L waves further away.

EARTHQUAKE FAULTS.—In the Californian Earthquake of 1906 a single great fault, now called the San Andreas fault, over 400 miles long, developed along the west coast of the United States. The strip of country bordering the fault on the west side was moved northward as much as 10 feet, and the zone to the east was displaced as much as 6 feet in some places to the south—the total maximum displacement being as much as 16 feet at the fault. Places on the west side, 30 miles from the line of the fault, were found to be displaced 2 or 3 feet; while stations on the east, about 10 miles from the fault, suffered no displacement. In addition to the lateral movement, there was field evidence of a relative up and down displacement on opposite sides of the fault at various places.

Similar phenomena were observed in the Mino-Owari (Japan) Earthquake of 1891. At once place in the Neo valley at Midori, near Gifu, the fault scarp crossed a road and dislocated the road laterally to the extent of 13 feet and produced a vertical drop, between the severed portions, of no less than 20 feet; this fault was traceable for over 40 miles.

In the case of the Assam (India) Earthquake of 1897, measurements made along one of the faults, the Chadrang fault, showed that there

had been practically no lateral shift, but that the vertical displacement, although variable, was as much as 35 feet in one place. The movement appears to have been confined to the uplifted side only. Details of this fault are so interesting that it is perhaps as well to describe them (see "The Origin of Earthquales," by C. Davidson, 1912, pp. 88–92, price 1s., or the original account by R. D. Oldham in *Mem. Geol. Surv. India*, Vol. XXIX, pp. 138, 147).

The fault, which has been traced for 12 miles, follows the valley of the Chadrang River and trends in a north-north-west to south-south-east direction; the river flows northward. The displacement of the rocks is always higher on the east (both papers above give a sketch). Where the river crosses the fault-line from east to west, there is a waterfall; where the stream meets the fault from the opposite direction, the water is impounded and forms pools. Pools have also been produced on the west side of the fault where tributary streams encounter the fault. The large pools (two) appear to lie at points where the fault has no appreciable throw, and it is concluded that a depression of the ground has occurred whereby the gradient of the stream has been reversed. The figures in the sketch indicate the amount of vertical displacement in feet. In two places it is seen that there is no evident displacement. In one place the throw has been measured as 35 feet. In both directions the trace of the fault is lost towards the north beneath thick alluvium, and to the south in thick jungle.

From what has been said in connection with these earthquakes faults, it is evident that no structure of human construction could resist the shear forces which have been exerted; everything would be sheared along the zone of shift; roads, railway lines, pipes, etc., would be elongated or shortened according as they crossed a zone of lateral shearing from right to left or left to right. This has been ably summarised by the Californian Earthquake Committee as follows (see Fig. 12):

"A line which crosses the zone of shearing from left to right (1) will be shortened, while if it crosses from right to left (2) it will be lengthened. The amount of shortening (*s*) or lengthening (*l*) will be equal to the total relative shift of the fault, multiplied of the cosine of the cute angle (*a*) between the line and the zone of shear."

SURFACE UNDULATIONS.—The Raleigh or L waves previously mentioned radiate from an epi-central tract, generally with diminishing amplitude and increasing wavelength; these waves have been repeatedly observed during great earthquakes. The estimated dimensions of their amplitude, length, periodicity, and velocity seldom agree in two earthquakes. The amplitude appears to vary from a few

inches in slight shocks to more than 3 feet in severe earthquakes. Measurements of wavelengths are computed at from 30 feet, where the intensity is great or the underlying rock consolidated, to 200 yards in loose wet ground. The periodicity is said to vary from 15 oscillations a second in solid rock to as little as 5 per second in incoherent alluvium. The velocity of transmission rarely appears to exceed 4 to 5 kilometres (roughly 15,000 feet) per second. However unsatisfactory these figures may be for seismographic calculations, they assist us in appreciating the magnitude of the forces released. There is little doubt that the nature of the strata immediately below the surface greatly modifies the amplitude and speed of these surface undulations. Solid rock which possesses considerable elasticity naturally allows of a quicker rate of travel, and the waves must pass

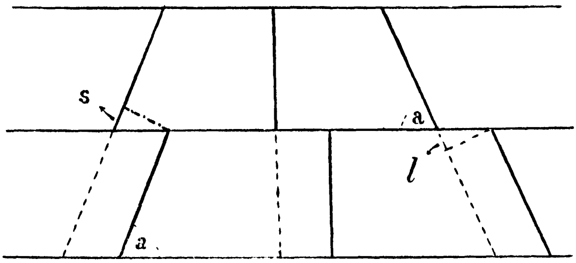


FIG. 12.
Plan of fault intersection.

like the ripples on the sea, but incredibly fast to be gauged by an observer. In loose wet alluvium with no elasticity there is appreciable lag, and the undulations evidently resemble the swell of a choppy sea; the rapid shaking movement, however, tends to consolidate the incoherent material, and, by expelling water and sand and liquid mud, produces the craterlets and shrinkage crevices so well known in connection with earthquakes which traverse alluvial tracts. It is to the oscillations induced in the rails by the waves and not to any compressional effect that the twisting of railway lines is ascribed. This evidence is often erroneously regarded as indicative of crustal shortening. It indicates an oblique travel of the seismic waves.

Most large and lofty buildings, however well constructed, are, relatively speaking, hollow or cellular fragile structures which, if constructed on loose or "made ground," must be subjected to very severe shaking during the passage of earth-tremors vibrating even one inch to and fro or any direction. If the earthquake is severe, it is almost impossible for such buildings to escape destruction. Low structures may be little damaged, but slender chimneys, spires, turrets

and clear, high walls, etc., invariably fall. Light wooden dwelling-houses, if well made and founded on piles, although as much shaken as masonry buildings, frequently escape structural damage. If the posts simply rest on supports and are not embedded, the damage is said to be still less, but this is the evidence of almost a single house in Tura, Assam. Brick buildings, however well bonded, generally crack in various places by the opening of the joints between individual bricks, especially along the horizontal jointing; parts of the walls may fall, but the building is seldom reduced to a pile of debris. Stone structures appear to crack at every joint, particularly if the stone is square dressed and in large blocks. In the case of mixed sizes of blocks, whether squared or not, the cracking is unavoidable, as the heavier blocks, with the velocities imparted to them, work free and invariably cause the building to fall in hopeless confusion.

The above remarks are chiefly in reference to structures built on alluvial or *made ground.* In the case of buildings founded on solid rock, the damage done is very much less. This has been well illustrated on several occasions. In the case of San Francisco during the Californian Earthquake of 1906, the evidence was very good. The city is built on solid rock, natural alluvium and "made ground." The destruction showed that the character of the material on which the foundations were made was a far more potent factor in determining the havoc wrought than nearness to the fault which had caused the earthquake. (See *Report of the Californian Commission*, Vol. I, pp. 220–245.)

"This is not a question of the transmission of vibrations, for, on account of the higher elasticity of solid rock, it would transmit vibrations far better than alluvium; and, indeed, as the alluvium occupies limited and comparatively shallow basins in the rock, the vibrations are always transmitted from a distance through rock, and the question really to be answered is: how are the vibrations modified in a basin of alluvium so as to make them more destructive than without this modification?" (*Ibid.*, Vol. II, p. 49.)

To an engineer the question is, how to minimise the effect of earth tremors on structures which must be on alluvial ground. From the analogy of the steadiness of a great ocean liner in a moderate sea, the answer would appear to be one depending on the rigidity and massiveness of the foundations of the structure. It would appear reasonable to suppose that a heavy concrete raft would by its weight (inertia) remain more or less stationary on the pulsating alluvium during the passage of an earthquake of short duration. If such a foundation, however slender or elaborate, can be included in the estimates of a building, it would, by its immovability, safeguard the superstructure it carried. The splendid white marble Victoria Memorial

M

in Calcutta was erected on just such a concrete raft as has been suggested above. It forms the foundation for the walls carrying the great dome.

The superficial nature of these surface undulations has received considerable support from experiments carried out in the seismic areas of Japan. It was found by experiment that in an excavation only 20 feet in depth the wave motion of the earth-tremor is very much less than it is at the surface. It is true that earthquakes are rarely felt underground in mines, even where they are shallow. However, as will be seen later, much depends on the distance of the mines from the epicentral tract. The observation is of importance, at any rate to the engineer, as at this depth (20 feet) he would be able to establish somewhat lighter concrete foundations than the heavy raft recommended above. Observations by the author appear to indicate that a deep wide trench, such as the moat round a fortress, appears to shelter the area immediately behind it. If this is true, protection of special areas of small extent might be protected in the same way.

It has been stated previously that there may be more than one centre of origin or focus from which the impulse of an earthquake initiates. If there are two such foci at some distance apart, two primary waves will result, producing two epicentral points from which two surface waves will originate. A pillar or tall structure subjected to two such impulses from different directions may have a rotational movement developed, and may suffer from the results of the torsional strain by being twisted. Evidence of this has been obtained from various twisted monuments and tombstones in both the Assam region and the area severely affected in California by the earthquakes of 1897 and 1906, respectively. The phenomenon is not at all uncommon, evidently, and in areas subject to earthquakes it would therefore seem advisable to bond the horizontal as well as the vertical joints in masonry work so as to obtain greater resistance to horizontal shear stresses; this is particularly desirable in the construction of high retaining walls which are normally subject to the horizontal thrust of impounded water or "running ground," and which may have been built in a seismic region.

Discussing twisted pillars as a result of earthquakes, C. G. Knott (see "The Physics of Earthquake Phenomena," 1908, pp. 20, 21) says:

"This vorticose movement, which at first sight seems to be proved by such effects, has not been accepted by some authorities. As is well known in dynamics, a simple impulse or blow acting on a body will cause that body to rotate if the impulse does not act through the centre of mass. Hence a succession of blows in varying directions may

easily cause a rotation in a body resting on, but not imbedded in, the soil. But it is difficult to escape from the belief that rotation of an object like a pillar or tombstone which is imbedded in the soil is an effect shared by the ground itself.

"Indeed, how can we have in the ground a succession of blows, varying rapidly in direction, without something of the nature of a whirling or vorticose motion accompanying it?"

The author admits the probability of vorticose movements of the ground during an earthquake and agrees that a rotational effect must result if these vibrations are made resultant in a horizontal plane. He, however, draws attention to the fact that nuts work loose on apparatus enclosed in cases during a journey due to the continuous vibration and jolting of the train. His observations of twisted pillars and displaced stones—the result of earthquakes—show that the plane of rotation is generally the lower surface of a single stone slab or block or of a mass of well-bonded masonry. It is his opinion that this plane of movement readily develops, due to easy separability when an independent oscillation is induced in the mass above it. Thus the mass becomes free to move horizontally, and such movement must generally become oblique or rotational.

My colleague, Dr. A. M. Heron, observed that heavy-roofed mud buildings, although only single-storied, had generally collapsed in the Baluchistan Earthquake of 1909. He also records how steel structural supports, such as those of large water tanks at the railway stations, remained intact, after the shock while the covering brickwork walls formed a mound of debris below (see *Rec. Geol. Surv. India*, Vol. XLI, Part I, 1911). A curious fact which has been repeatedly noted in connection with buildings damaged by earthquake shocks is that sheets and panes of glass in doors and windows frequently remain intact, although the structures are severely shattered. This has been found true in America, India, and elsewhere. The direction in which a wall or a statue falls during an earthquake is often of considerable value and interest. It generally happens that a wall will fall away from the side on which it is buttressed or otherwise held in support. In the case of a statue the fall is usually at right angles to the long axis of its rectangular or oval sectioned pedestal. The actual side is dependent on the relative freedom in opposite directions. Thus the travel of the seismic waves may even be at right angles to the direction of fall of a statue and oblique to that of a fallen wall.

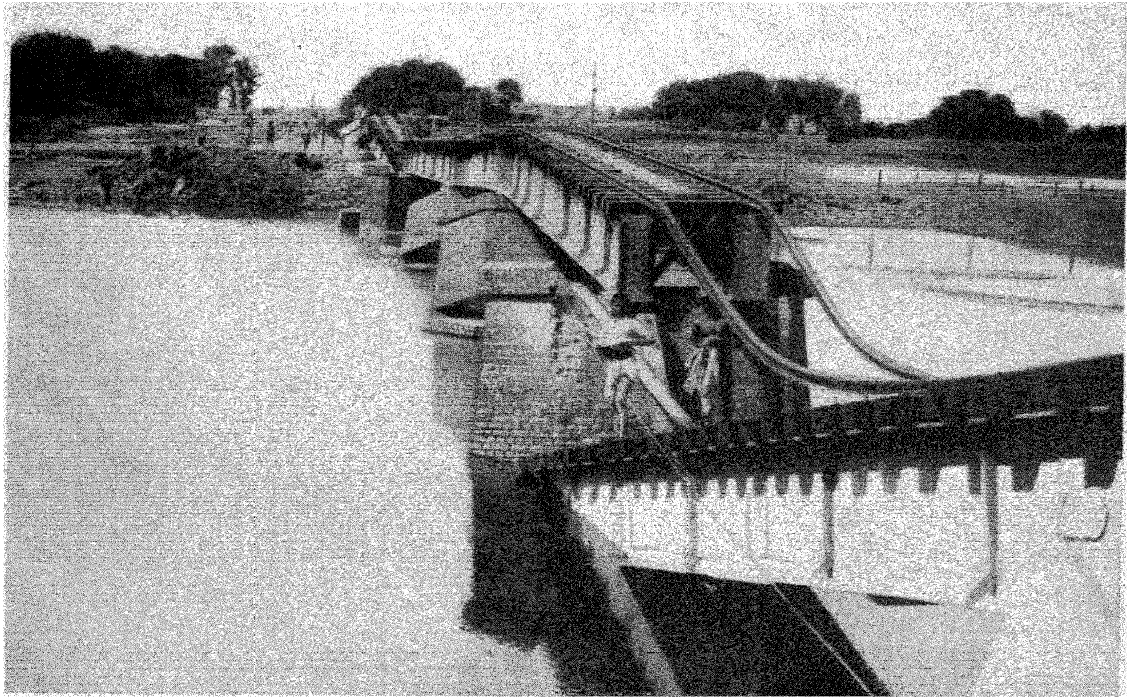
UNDERGROUND OSCILLATIONS.—As already indicated, the surface L waves are seldom felt beyond depths of 200 to 300 feet in underground workings away from shafts. The to and fro movements produced by the P (primary) waves of earthquakes are relatively small—estimated at from 2 to 6 inches at most. As these waves travel

further and further away from the focus of the earthquake in an oblique direction towards the surface, these oscillations become less and less in degree, owing to absorption by the material they traverse, some rocks having greater elasticity than others. As a result of experiments by detonations in deep mines, Professor Fouqué and M. Michel Lévy (*Memoires Acad. Sci. Inst., France*, tome XXX, 1889, p. 77) found that the rate of transmission in granite ranged from 3,141 to 2,450 metres per second; in coal measures from 2,526 to 2,000 metres per second; in normal sandstones (Permian) about 1,190 mètres per second; in limestone (Cambrian) 632 metres per second; and in soft (Fountainebleau) sandstones about 300 metres per second. It is therefore possible that in two equally deep mines—one, say, a metal mine in granitic rock and the other a coal mine—both equidistant from the focus of an earthquake—the tremors may be felt in the metal mine and yet not be noticed by the coal miners. If in the case of the sedimentary strata the structure was such (deep synclinal) that beds of poor conductivity (weaker elasticity) were interposed in the path of the waves, the oscillations would be still less appreciable in the coal mine.

In the preface of his report (*Mem. Geol. Surv. India*, Vol. XXIX, 1899, p. 15), R. D. Oldham says that

"the 1897 earthquake was not felt underground in the mines of the Bengal coalfields; it was felt and caused some damage in the coal mines at Makum in Upper Assam; but these mines are really overground, being driven into the side of a hill and not descending below the ground surface level, the conditions are, therefore, not strictly comparable to those of a mine sunk in open and tolerably level country."

As to why the P and S vibrations should not induce movements, it is difficult to see. However, the experiences both in the Makum collieries and those of Giridih, Raniganj and Jharia in the Damodar valley were similar in the case of the Dhubri Earthquake of the 3rd July, 1930. In the former area, part of the roof fell in in the workings of Tirap colliery, Ledo, and in the latter area nothing was noticed below ground except in one case. The roof weight came on suddenly, and resulted in the crushing of coal pillars in XV seam, Bhulanbararee colliery, Jharia, where the workings are at a shallow depth not far removed from steeply inclined strata along a strong fault. A far more serious state of affairs in these Damodar valley coalfields due to the earthquake of the 17th January, 1934—the disastrous Bihar Earthquake—has been the wrenching along the fault planes, thus permitting movement in the underground water. Workings on the rise side of faults have been thus providentially drained, while those to the dip of such faults or at lower levels have had to cope with seriously



Per favour "The Statesman," Calcutta.] EARTHQUAKE DAMAGE. [*Photo by "The Statesman,"* **Calcutta.**

The earthquake waves evidently travelled along the bridge and the oscillations have caused the piers to fail. The failure is due to lack of "break joints" in a horizontal plane.

SITAMARI RAILWAY BRIDGE, AFTER 1934 BIHAR EARTHQUAKE.

[*To face page* 164.

enhanced water difficulties. In connection with the cable subway under the Hughli River, the Calcutta Electric Supply Corporation wrote as follows (Dhubri, 1930, Earthquake):

"The following information may be of interest to you; it is the experience of the men who are working on the shaft for our river tunnel in the Botanical Gardens. Four Punjabis were working on a staging in the shaft, 8 feet in internal diameter, about 50 feet below ground level and in compressed air. The skip used for raising and lowering the men was suspended ready for the men to step into it in case of anything happening. At about 2.57 a.m. (Calcutta time) one of the men seized a bamboo ladder which is attached to the side of the shaft and caught one of the other men who might have fallen, and held him. The other two men were thrown against the side of the shaft opposite. . . . It should be mentioned that when the quake started the skip began to swing."

EFFECTS ON WATER.—Mention has already been made of the changes effected in the underground water of the Jharia coalfield by the recent Bihar (1934) Earthquake. It is, however, quite a common observation in alluvial plains to have considerable changes in the condition of wells. In many instances the wells are choked with sand after copiously discharging water and sand. That subsidence occurs in such cases is clear from the settlement of the masonry of the well—often the whole of the wall is found sunk through the cemented floor about the well. Similarly, curious craters are found in alluvial areas from which water and sand was ejected during an earthquake. These phenomena are very simply explained. The alluvium often has thick beds of soft sand, and the whole is full of water and quite unconsolidated. With the vibrations and shaking by an earthquake, the whole moves like a jelly. The tendency is for the water to be ejected and the sand, etc., to become firm. The ejected water appears from fissures and craters and carries sand and mud with it and any light matter, such as pieces of lignite or coal, that may have accummulated with the alluvium. Earthquakes are known to be frequent in the ocean floor and are recorded on seismographs, and if close to a coast, are felt both as earth tremors and the subsequent sea waves. These waves from the sea may be very large and arrive like a tidal flood and sweep the coasts with great damage to buildings and shipping. Out at sea they may not be noticed on board modern liners, but if movements have occurred in the sea floor across lines of submarine cables, these may be injured, and even severed. Details of the interruption of the Atlantic cables near Nova Scotia after a submarine earthquake are available in several papers.

SEISMOGRAPHS, ETC.—It is usual to arrange seismographs to take records of all three types of waves from any direction. The

P waves come with a to and fro movement (longitudinal or compressional), and can only influence an arm free to oscillate in their plane such as a pendulum, whereas the S waves (transverse and distortional) will best affect a horizontally placed recorder, and the L waves are

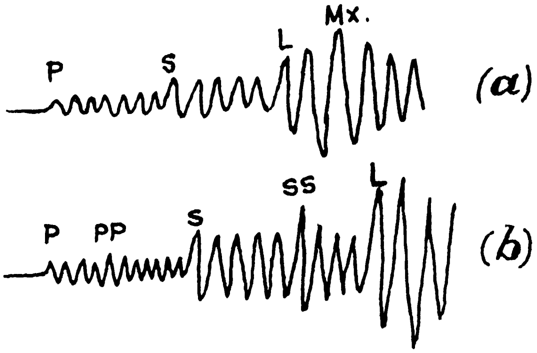


FIG. 13.
Seismograph record.

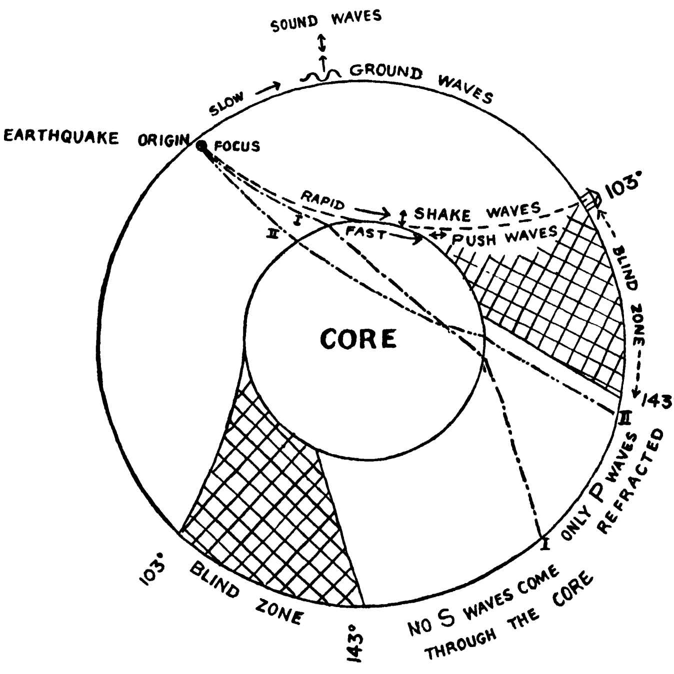


FIG. 14.
Travel of earthquake waves.

able to influence a horizontal recorder capable of vertical movement or a pendulum. It is possible to combine all these requirements in the construction of a single apparatus, but it is not at present possible to have an instrument which is capable of recording very faint tremors, and, being automatically protected, also able to receive the vibrations of a severe earthquake at close range. Damping vanes are in use, but it is still customary to provide a recording station with two, or perhaps three, different seismographs—one for the P and L waves, another for the S and L waves, and perhaps a third for the S and L waves of greater intensity. The characteristics of the seismograph records are now almost too well known to be described—there is the first weak oscillation when the P waves arrive, then somewhat bigger swings indicating the arrival of the S waves, and then big movements showing the L waves in action. Actually these records are not so simple, and more than just these three sets of waves are seen. There is believed to be proof of the successive layers of the earth's shell from these other waves which are considered as reflected P and S waves from the successive planes of junction between the layers—one pair reflected and another refracted below and reflected from the plane next below, etc.

EARTHQUAKE QUESTIONNAIRE.

The type of questionnaire usually circulated for the collection of information immediately after an earthquake asks for :

(1) Time of occurrence, standard time, if possible.

(2) Duration of shock in seconds.

(3) Situation of observer, whether in or out of doors, asleep or awake, sitting or standing, etc.

(4) Number of separate shocks, if more than one was felt.

(5) Were any unusual sounds heard either before, during, or after the shock, and what did they resemble ?

(6) What was the intensity of the shock ? Whether strong enough
- (*a*) To be felt by everyone.
- (*b*) To be felt only by persons at rest.
- (*c*) To make doors, windows, etc., or loose objects rattle, and floors creak.
- (*d*) To make hanging objects swing.
- (*e*) To move observer's seat.
- (*f*) To throw down loose objects.
- (*g*) To crack the walls of buildings.
- (*h*) To cause greater damage (to be specified).

SCALE OF EARTHQUAKE INTENSITIES.

Approximate Intensity.	Oldhams Scale (India).	Rossi-Forel Scale.	Mercalli Scale (Italy).	Omori Scale (Japan).	
Epicentral Region— Innermost isoseist in which there was practically universal destruction of stone and brick buildings	No. 1	X	X	VII	acceleration greater than 4,000 mm. sec/sec.
Second isoseist serious damage to masonry and brick buildings in some cases amounting to destruction	No. 2	IX	IX	VI	acceleration about 4,000 mm. sec/sec.
Third isoseist earthquake violent enough to damage nearly all brick buildings ..	No. 3	VIII	VIII	V	2,500 mm. sec/sec.
Fourth isoseist earthquake felt by all, few buildings damaged, but loose objects disturbed	No. 4	VII and VI	VII and VI	VI	2,000 mm. sec/sec.
Fifth isoseist shock generally noticed not severe enough to cause any damage ..	No. 5	V and IV	V and IV	VII	1,200 mm. sec/sec.
Sixth isoseist earthquake only noticed by people sitting or lying down or otherwise favourably situated	No. 6	III and II	III and II	II	900 mm. sec/sec.
Seventh isoseist not noticed except by very sensitive people or recorded on seismograph	No. 7	I	I	I	300 mm. sec/sec.

CHAPTER IX

STABILITY OF HILL-SIDES AND CLIFFS

STABILITY OF HILL-SIDES.—Landslides are familiar troubles in most countries where roads, railways, and canals have been made through hilly country. The difficulty of keeping the Panama Canal open was largely due to the unstable condition of the sides in certain sections of the cutting. The expense involved in holding up these unstable sections of a road or canal is always considerable if the material cannot be permanently held. (Photograph XI.)

Landslips occur when by natural processes the unconsolidated loose materials or the jointed masses of rock of a hill-side detach themselves and slide down. The loose material—soil, gravel, etc.—on most hill-slopes tends to creep or slide down to a lower level. If the hill-slope exceeds the angle of repose of this material, a sudden slip or a gradual creep will take place, unless the loose material is held up by vegetation or by artificial means. The slope, however, will be unstable if unsupported.

CREEP.—The tendency to slide is so strong that on bare, fairly steep slopes in which bedded rocks are hidden by a few feet of soil, a drag is exerted on the underlying rocks. If the rocks are steeply inclined (see Fig. 15), the upper part of the beds may be bent over, and give quite an erroneous idea of the true dip of the strata. This structure is known as "terminal creep," and is sometimes of considerable importance to the engineer; for example, in Fig. 15, supposing a dam had been built across the valley, the impounded water would wet the incoherent material, thereby reducing its angle of repose, and cause it to slide into the reservoir. The movement of this material on the lower slopes would disturb the angle of repose of the material higher up and possibly result in other landslips, which might seriously reduce the volume of water stored in the reservoir. If a pressure tunnel had been put through the hill in the section shown in Fig. 15, the tunnel would certainly be choked and the supply of water cut off (see also Fig. 16).

EARTH LOADED WITH ITS OWN WEIGHT.—In a mass of earth, loaded with its own weight only, the gravitation of the earth

causes the vertical pressure; the vertical pressure causes a tendency to spread laterally; and the tendency to spread causes the conjugate pressure; therefore the vertical and conjugate pressures stand to each other as cause and effect, or active and passive, respectively; therefore the intensity of the conjugate pressure is the least which is consistent with the conditions of stability stated above, which therefore become:

Vertical pressure, $P_x = \omega x \cos \theta$
ω = weight of unit volume of earth,
x = depth below the surface,
θ = inclination of plane.

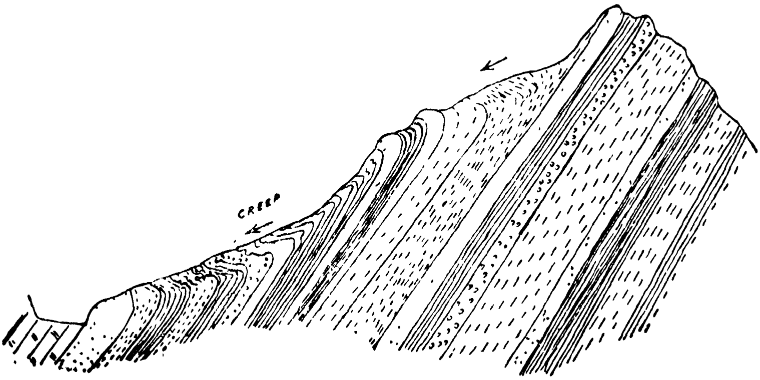


FIG. 15.
Terminal creep.

Conjugate pressure, parallel to steepest declivity.

(1) General case

$$P_y = \omega x \cos \theta \frac{\cos \theta - \sqrt{(\cos^2\theta - \cos^2\phi)}}{\cos \theta + \sqrt{(\cos^2\theta - \cos^2\phi)}}$$

(2) Horizontal surface, $\theta = o$, $\cos \theta = 1$, $P_x = \omega x$

$$P_y = \omega x \frac{1 + \sin \phi}{1 - \sin \phi}$$

(3) "Natural slope," $\theta = \phi$

$$P_y = P_x = \omega x \cos \phi$$

FRICTIONAL STABILITY OF EARTH—PRINCIPLE.—The resistance to displacement by sliding along a given plane in a loose granular mass is equal to the normal pressure exerted between the parts of the mass on either side of that plane multiplied by a specific constant.

$$(\text{q} = \text{the resistance to sliding}) \; \frac{\text{q}}{\text{p (normal)}} = \tan \phi = f$$

Theorem I.—It is necessary to the stability of a granular mass that the direction of the pressure between the portions into which it is

divided by any plane should not at any point make with the normal to that plane an angle exceeding the angle of repose.

Theorem II.—At each point in a mass of earth, the ratio of the difference of the greatest and least pressures to their sum cannot exceed the sine of the angle of repose.

(p_1 and p_2 greatest and least pressures)

$$\frac{p_1 - p_2}{p_1 + p_2} = \sin\theta \leq \sin\phi$$

$$\text{or } \frac{p_1}{p_2} \leq \frac{1 + \sin\phi}{1 - \sin\phi}$$

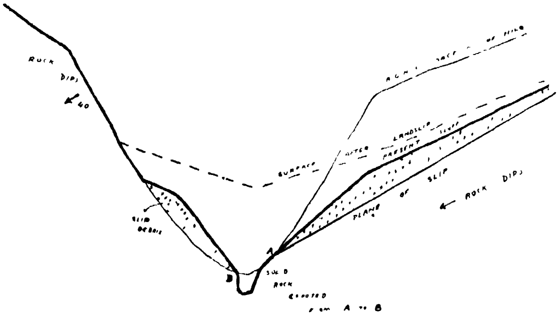


FIG 16
Unstable debris.

Theorem III.—The following is the expression of the condition of the stability of a mass of earth, in terms of the ratio of a pair of conjugate pressures in the plane of greatest and least pressures.

$$\frac{p}{p^1} = \frac{\cos\theta + \sqrt{(\cos^2\theta - \cos^2\theta_1)}}{\cos\theta - \sqrt{(\cos^2\theta - \cos^2\theta_1)}} \leq \frac{\cos\theta + \sqrt{(\cos^2\theta - \cos^2\phi)}}{\cos\theta - \sqrt{(\cos^2\theta - \cos^2\phi)}}$$

COEFFICIENT OF FRICTION.—The friction which a given pair of solid bodies, with their surfaces in a given condition, are capable of exerting, is simply proportional to the force with which they are pressed together (" Applied Mechanics," Rankine, 21st Edn., 1921, p. 209). The coefficient of friction of repose, f (*i.e.* tan ϕ (angle of repose) = coeff. of friction, f) gives the angle at which a plane surface can be tilted before movement takes place. In this connection the following coefficients of friction are of value. (See page 172.)

These coefficients have not been accurately obtained for the various kinds of rocks, but sufficient is known to enable the engineer to know the danger angle of such strata.

The subject of earth pressure for loose material is mathematically dealt with by M. A. Howe in his book " Retaining Walls for Earth," 1907 (John Wiley & Sons).

Materials.	f	ϕ	$^1/f$
Dry masonry and brickwork	0.6 to 0.7	31° to 35°	1.67 to 1.43
Masonry and brickwork, with damp mortar ..	0.74	36°30′	1.35
Timber on stone	about 0.4	22°	2.5
Iron on stone	0.7 to 0.3	35° to 16°40′	1.43 to 3.33
Timber on timber	0.5 to 0.2	26°30′ to 11°20′	2 to 5
Timber on metals	0.6 to 0.2	31° to 11°20′	1.67 to 5
Metals on metals	0.25 to 0.15	14° to 8°30′	4 to 6.67
Masonry on dry clay ..	0.51	27°	1.96
Masonry on moist clay ..	0.33	18°15′	3
Earth on earth, dry sand, clay and mixed earth ..	0.38 to 0.75	21° to 37°	2.63 to 1.33
Earth on earth, damp clay ..	1.0	45°	1
Earth on earth, wet clay ..	0.31	17°	3.23
Earth on earth, shingle and gravel	0.81 to 1.11	39° to 48°	1.23 to 0.9
Hard brick on hard brick ..	0.70		
Concrete blocks on concrete blocks	0.65		

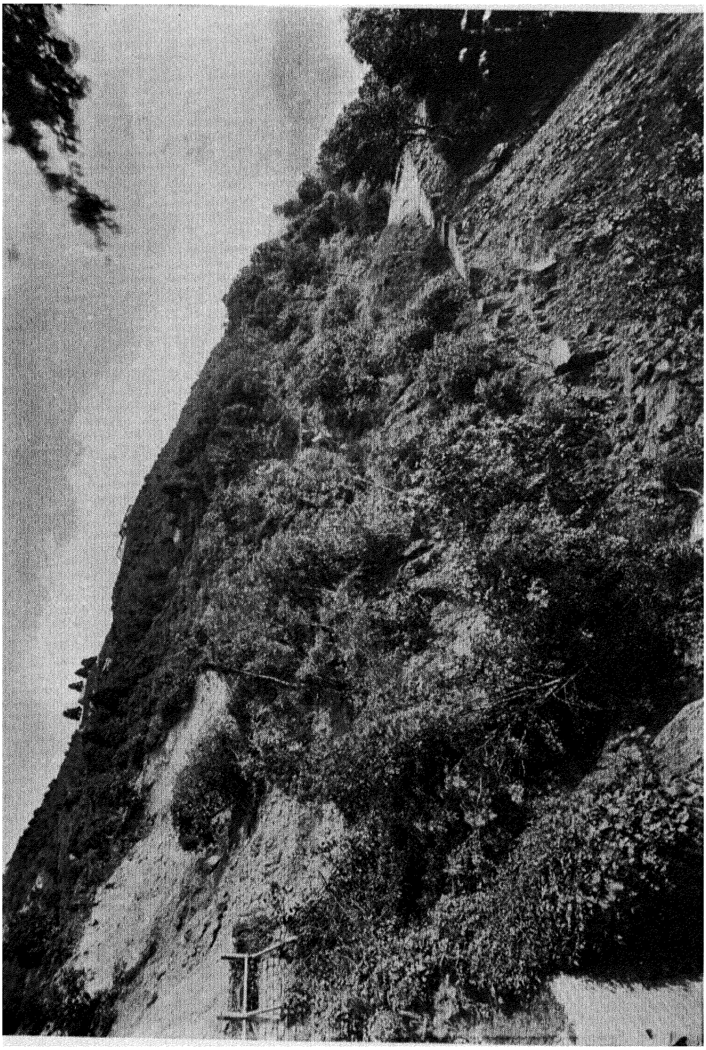
(Rankine, p. 211, after General Morin.)

In the same treatise this writer gives the angle of repose of various other loose materials as follows :

		Average weight in lbs. per cubic feet.
Compact earth (clay)	50°	70–76
Moist earth (loam)	45°	
Gravel	40°	82–92
Dry earth (shaken)	40°	
Dry sand	38°	
Coal bituminous (broken) ..	35°	47–52
Sand, quartz (dry)	35°	90–106
Anthracite (broken)	27°	52–56

The angles of repose of coke in various-sized fragments are elaborately discussed in an appendix to Wagner's book, "Coal and Coke."

Coarse-textured rocks, conglomerates, grits, sandstones, quartzites, when not badly fissured and not interbanded with soft rocks, appear to have an angle of repose as high as 35° or more. Soft rocks, fine clay-slates, slates shales, etc., have a limiting angle at about 28° when dry, and less when wet. The worst condition occurs when interbanded hard and soft rocks are found tilted at about the angles given above.



Per favour D.G.S.I.] TYPICAL LANDSLIP. [*Photo by Sir Thomas Holland.*

Partly due to soil creep when waterlogged by heavy rain after a period of dry weather, the slip has involved a road across a length of several yards and down the slope nearly 60 feet.

LIMBU JHORA, NEAR MARYVILLE, DARJEELING.

FRICTIONAL STABILITY OF PLANE JOINTS.—In a structure composed of a number of pieces connected only by contact at plane surfaces (masonry, brickwork, strata, etc.), it is necessary to stability that the obliquity of the pressure should at no joint exceed the angle of repose.

A plane joint which has no tenacity (mortar, cement, etc.) is incapable of resisting any force, except a pressure, whose centre of stress falls within the joint and whose obliquity does not exceed the angle of repose.

ANGLE OF REPOSE.—The greatest angle of obliquity of pressure between two planes which is consistent with stability is the angle ϕ whose tangent is the coefficient of friction (" Applied Mechanics," Rankine, 21st Edn., 1921, p. 210).

The angles of repose ϕ of various materials, sand, clay, etc., are fairly well known within certain limits; *i.e.* for earth and loam it varies from 30° to 45°; for moist sand it is about the same—30° to 45°; in clay it varies from 25° to 45°; gravel 30° to 40°; dry sand 25° to 35°; wet sand 15° to 30°, etc. Consequently, these materials will not remain on hill-slopes of the same inclination as their angle of repose. The " creep " is greatest in very wet weather, particularly after long, dry spells. The expedients of planting shrubs, cutting vertical drains, etc., to hold the incoherent material, are well known to all engineers. The cutting of a herring-bone system of channels down the slope, or special drainage tunnels to take off the water, are other methods of protecting hill-sides. However, this opens up an aspect of the subject in which the remedy sometimes proves worse than the disease—for, in some cases, by draining away the water from moist material, the angle of repose may be decreased and larger slips may be caused. This is said to have occurred in the Panama Canal. When hard, massive rocks, granites, dolerite or thick beds of sandstone, quartzite or limestone, are exposed on hill-slopes, the hill-side may be perfectly safe at all angles up to vertical precipices. A hill-side with thick bedded rocks may, however, be liable to enormous landslips. The conditions for these depend on the direction in which the strata is tilted, their degree of inclination, and the nature of the beds involved. There is always a tendency for an upper bed to slide upon the stratum below—particularly if the strata consist of alternating hard and soft beds. The principles are the same as with loose materials, although the constants naturally differ.

MUD SLIPS.—Much trouble has been caused by great landslips in the Black Canyon section (Thompson River) of the Canadian Pacific Railway in British Columbia (R. B. Stanton, *Min. Proc. Inst. C.E.*, Vol. CXXXII, pp. 1-19). The line runs on terraces of a

peculiar hard silt which consist of coarse and fine sand, coarse and fine grains of disintegrated felspar, and kaolin as a matrix. Under the action of *running* water the aggregate components, sand and felspar grains, are washed out, leaving a plastic clay to protect the exposed surface against further scour. The silt is underlaid by a thick deposit of gravel and boulders with a matrix of boulder clay. This glacial material in turn overlies Cretaceous strata, but these rocks do not affect the stability of the terrace slopes.

The overlying silt is like a soft sandstone, and when struck with a hammer rings like stone. A large piece of the silt, however, if placed in a basin of water, dissolves after a few minutes and falls down, not in a lump as clay, but mingles with the water, forming a semi-fluid mass like thick pea-soup. The same soft mixture was observed oozing out at many points along the foot of the slide, forced out by the pressure above.

Sir Guildford Molesworth, when constructing the low level line to the Crystal Palace, found that London clay, when wet, becomes of such a fluid consistency as to flow away from the slope of the embankment and bulge upward.

A clay dug from a well in the Chenab River, Punjab, was strong and hard and tenaceous when kept in water; if dried, it became as hard as stone and could be broken up only with difficulty. This dried material, if placed in water, melted like sugar.

The great slips which occurred on the railway between Karachi and Quetta (Baluchistan), near the Mud Gorge, are said to be due to the disintegration of gypsum shales. Nothing could be done to stop the slips—the rails had to be slewed round after each slide. Drainage was found the most effective remedy.

The study of a landslip involving alluvial material or rock debris often shows that it resembles a glacier. There are three characteristics—a slip face or scarp at A corresponding to the *nevé*; a flat at B corresponding to the surface of the glacier, and a bulge of C where *seracs* are common in glaciers. The movements are downward at A; almost horizontal at B; and outward, perhaps upward, at C.

In Figs. 17 A and B other features of similarity show themselves: thus, a subsidiary scarp may be seen at F corresponding to the great ice fissures, *Bergschrund*, which occur at the junction of a glacier and the nevé—the lateral scarps H, H, occupying the position of the longitudinal *crevasses* seen on the margins of glaciers. The movement of the mass at F is vertical (down), while at H, H, the tendency is to slide or shear sideways (horizontal and down). (These features were (1924) seen on the slipping hill-side at Murree, the Military Headquarters of the Indian Northern Command. Although the "slip

area " was on the move, moving very slowly with intermittent slipping, there is no danger of the whole suddenly sliding. The plane of sliding is gentle and the debris was gradually jamming itself between two converging spurs.) However, it is evident that to build on the slip at places in the vicinity of F or H, H, is to court disaster. The

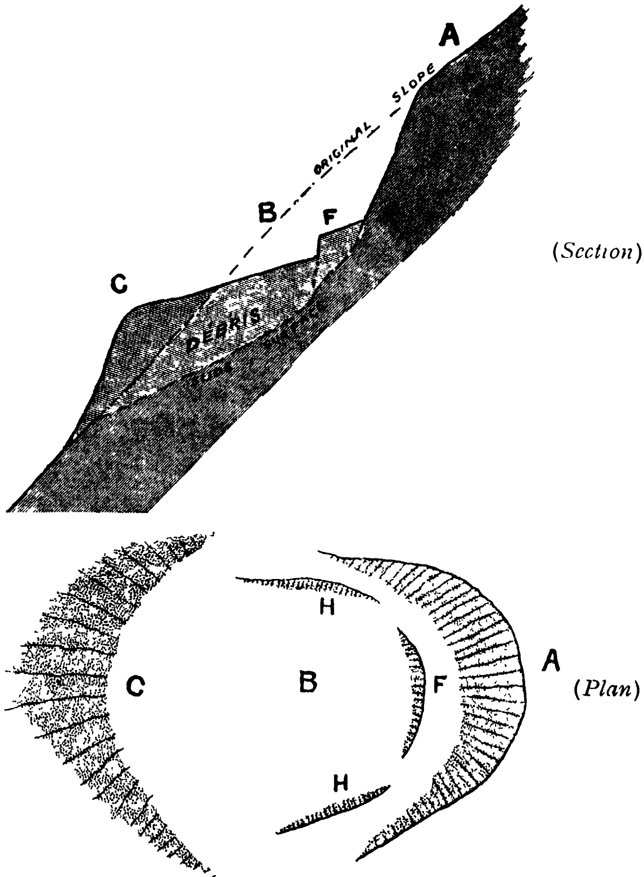


FIG. 17.
Structure of landslips.

safest place would be in the middle of the flat B, but the wisest plan would be to leave the area alone for a few years.

INCLINED BEDDED ROCKS.—Figs. 18, 19 and 20 show sections of a hill-side with inclined strata. It is clear that the dips must be in the same direction as the slope of the hill in order that the overlying rock masses can slide clear and form a landslip. The danger is naturally greater in thin beds, because there are so many more inclined planes on which the slips can take place. In Fig. 18 the beds are shown dipping at an angle greater than 30°, with a free out-

fall towards the river; consequently the conditions are present for a great landslip. Fig. 19 shows a hill-slope with an inclination of 40° with beds dipping at about 32°. The beds consist of hard, schistose

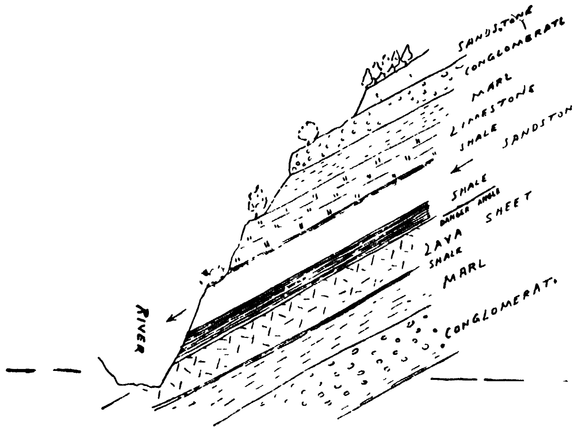


FIG. 18.
Unstable hill-side (bedding planes).

quartzites with intercalated layers of clay-slate. In this case a portion of the hill-side is dangerous and may be loosened by cutting a road in the concave part of the slope. Fig. 20 represents a section where

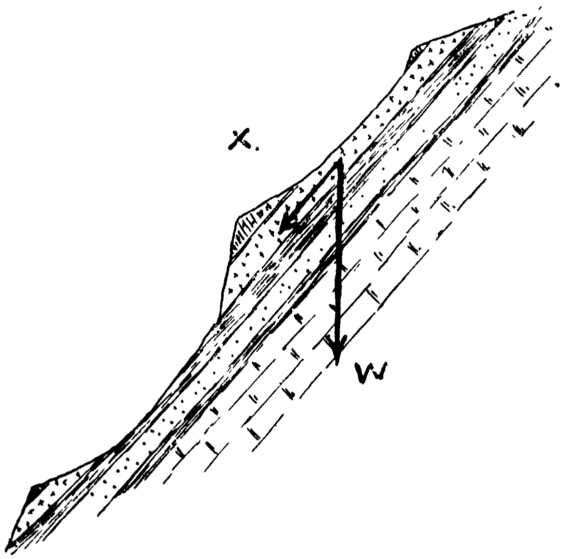


FIG. 19.
Slope liable to slips.

the dip of the strata is greater than the slope of the hill. The hill-side, although quite steep, is probably quite safe, because each successive bed is held up by the one below it. There is no free outfall.

JOINT PLANES.—If the rocks dip into the hill, the conditions are better for safe hill-sides, unless a system of joint planes is present (see Fig. 22). Joint planes may often function as inclined planes if they are tilted towards the valley at suitable angles. Occasionally

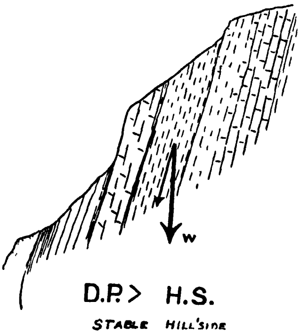


FIG. 20.
Safe hill-side.

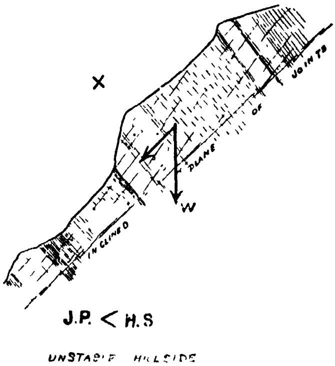


FIG. 21.
Unstable hill-sides (joint planes).

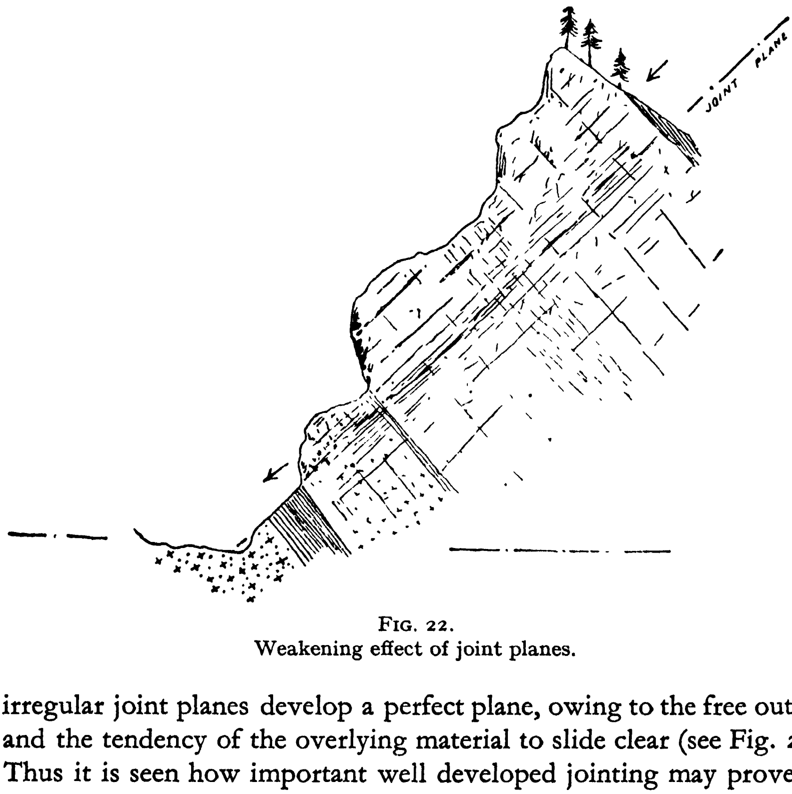


FIG. 22.
Weakening effect of joint planes.

irregular joint planes develop a perfect plane, owing to the free outfall and the tendency of the overlying material to slide clear (see Fig. 21). Thus it is seen how important well developed jointing may prove in questions of this kind. In Fig. 23 a number of unstable hill-sides are depicted. This sketch represents various examples of unstable hill-

slopes which were actually found in a reconnaissance survey of a projected railway alignment in the Ganges valley of Garhwal in the Himalayas. In the foreground, on the right, two terraces are seen cut by ravines. These flats, although composed of debris, are well drained and quite firm. Spur 1 shows steep in-dipping strata on what would have been a safe slope, but, owing to the system of joints, this

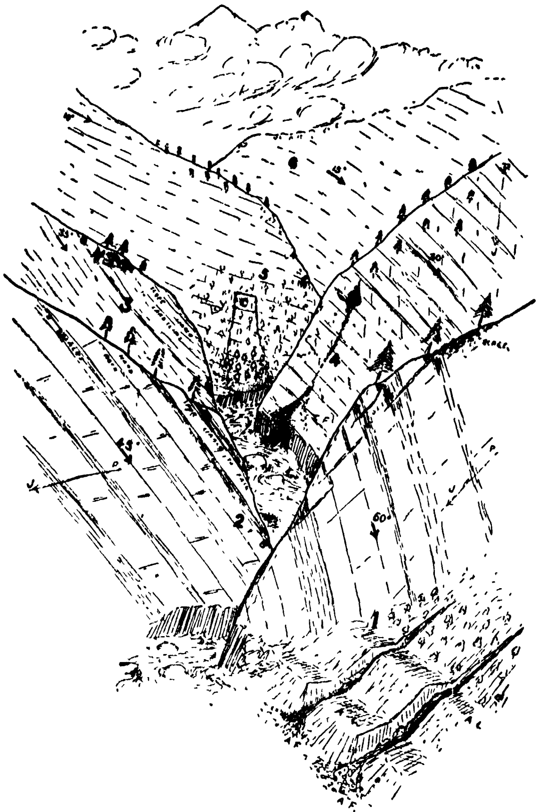


FIG. 23.
View of mountain slopes.

hill-side is liable to landslips. Spur 2 is clearly unsafe. The rocks dip steeply towards the river at a lesser angle than the lower slope of the convex spur, and are consequently in an unstable condition. Spur 3 is similar to Spur 2 in structure, and although the dips are a little less, the beds consist of hard, doleritic gneiss with interbedded, greasy, talc schists. The hill-side is perhaps more dangerous than that of Spur 2. Spur 4 is perfectly safe from a structural point of view, but a bad face of fissured rock is exposed from which, in times of frost, pieces split off and form scree. This face of rock could perhaps be easily sealed up by a small masonry wall. Spur 5 is of interest in that

PHOTOGRAPH XII.

Per favour D. G. S. I.] [*Photo by Dr. A. H. Heron and Mr. H.* ***Walker.***

UNSTABLE STRATA.

The rocks to the right of the bridge dip at 35° in the same direction as the slope of the hillside, which is 45°. Thus if the planes of stratification become lubricated the upper material A can slide forward on to the bridge.

SUSPENSION BRIDGE BELOW ALMORA, KUMAON, HIMALAYA.

[*To face page* **178.**

the soil and subsoil has moved under the influence of its weight on the steep slope, carrying with it a forest-covered hillside in a typical example of creep. The ominous bulge at the base first drew attention to the scar C above.

RIVER BENDS.—When considering hill-sides, it is necessary to examine the whole slope from the bed of the valley to the crest of the ridge, and to take into account the curves of the stream. A landslip is generally more quickly precipitated, when unstable conditions prevail, at those places where the river makes a concave bend to a projecting spur. In such cases, not only is there a free outfall, but the rocks are also free on either side. In a lateral valley the rocks are held in both directions along their line of strike.

As a general rule, therefore, it is best *to avoid, as far as possible, the side of a valley in which the rocks dip towards the stream at the danger angle, but less steeply than the hill-slope—particularly when the beds consist of interbedded layers of hard and soft rock.*

SLIDES IN THE PANAMA CANAL.—Of all the incidents that grew out of the peculiar geological conditions encountered in canal construction, perhaps none attracted wider public attention than the landslides. (See "Outline of Canal Zone Geology," by Donald F. Macdonald, *Trans. International Engineering Congress, San Francisco,* 1915, pp. 67-83.)

In the Culebra (Gaillard) Cut, there are four distinct types of slides recognised, due to (I) structural breaks and deformation; (II) normal or gravity slides; (III) fault-zone slides; and (IV) surface erosion.

(I) The largest and most important slides developed first as cracks or fissures, parallel or oblique to the line of the Cut, and then continued by the settling or outward tilting of the big blocks which had cracked off from the solid bank; finally the whole block disintegrated and sloughed down into the excavation.

The chief latent causes were (1) that the formations involved were of very soft, weak rocks, comprising massive, partly indurated, volcanic clays, very friable bedded tuffs, and soft, brittle and slippery, lignitic shales; (2) these rocks had been further weakened by faulting and some by joint and bedding planes; (3) an abundance of ground water had invaded this material whenever it was disturbed by movement or fissuring, and this greatly added to its mobility; (4) lignitic shale beds, especially where they dip canalward, were planes of weakness along which there was a strong tendency for the overlying material to slip; (5) the presence of a considerable proportion of chlorite particles in the volcanic clay rocks tended to lubricate the mass. The immediate cause of the slides was due to the over-steepness of the slopes where the banks were high and the rocks weak, and the large percentage of

ground water they contained. The vibrations generated by blasting near these high over-strained banks were also slide-producing factors.

The only really useful remedy for this type of slide consisted in making the slopes less steep by removing material from their upper portions. At first sight it might have seemed preferable to let the slides come into the excavation until permanent slopes were reached, thus saving the expense of much blasting; but deformation of this kind weakened the rocks far below the bottom of the excavation, and this weakened material required a much flatter slope than the angle at which it would have stood before being weakened by deformative movements. Further, as each block or mass crashed down, it

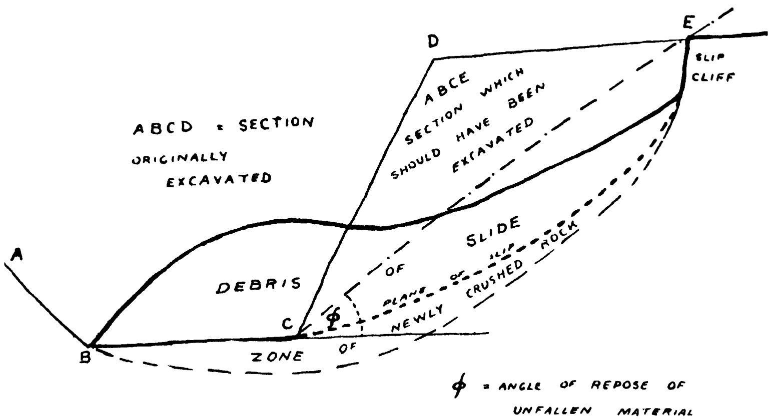


FIG. 24.
Panama landslide.

generally left behind not a gradual slope, but a steep face 40 to 82 feet or more high which greatly assisted in the generation of other slides (see Fig. 24). There was also the temporary obstruction of railway tracks and drainage ditches by some of these slides.

(II) The normal or gravity type of slide was due to several factors. Locally, along the Culebra Cut, porous material lies on top of relatively impervious clay shale, or igneous rock. Rain and ground water saturated the porous mass, but were impeded in their downward course by the relatively impervious rock. This caused a muddy slippery zone to form along the plane of contact between the pervious upper and impervious lower materials. Where this plane sloped towards the Cut, or where there was a thrust or head of pressure toward the excavation from higher ground in the rear, a slide of the normal or gravity type resulted. Where bedding and joint planes dipped towards the Cut, they greatly assisted gravity to wedge off rock masses.

This type of slide had certain distinguishing features. The rocks

were not deformed or weakened below the plane of actual sliding. The sliding material moved off a solid base, and this was not pulled down or squeezed out by the functional pull. No saving could be accomplished by removing material from the upper parts of such slopes. It was better and cheaper to let the slides run their course and remove the debris from the Cut. Drainage was almost the only remedial factor that could be applied to slopes having the structure and constitution described above. The Cucaracha slide was the most troublesome of this type.

(III) Fault zone slides were primarily due to weakened strata which had been sheared by faults oblique to the Cut. The mass of the rock in the acute angle which the fault plane made with the Cut occasionally had a large over-hang due to the dip or hade of the fault

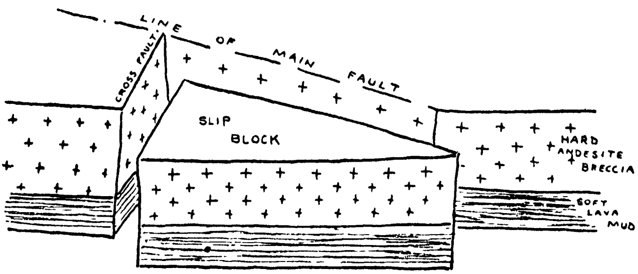


FIG. 25.
Slip due to faults.

plane. As the excavation was deepened, the tendency of the mass to slide forward steadily increased, until the strain overcame the resistance of the base of the block, and the whole fell forward into the Cut (Fig. 25).

This type of slope failure, unlike the others, occurred in rocks strong enough to stand a steep slope but for the diagonal fault zones. Slides of this character were not common, and the only remedy was to reduce the slopes in the vicinity of the fault planes and, where practicable, to prevent excessive water from percolating into weakened faulted material.

Fig. 25 shows a large mass fallen in this manner into the Cut near La Pita. Nearly 300,000 cubic yards of debris had to be removed from the Cut.

(IV) Slips due to scour and wash. It is estimated that 65,000 cubic yards of soft, easily-weathered rock unprotected by vegetation have been swept by the heavy downpours of rain into the Culebra Cut.

The growth of shrubs and the carpet of grass which has been planted, will greatly minimise the wash of the tropical rains. Such vegetation will probably not prevent subsoil creep on a large scale;

the only prevention for this is efficient drainage. In some horizons, the beds of the Culebra formation (Lowest Oligocene) are impregnated with iron pyrites (marcasite), and this material is liable to rapid oxidation, with the result that rocks heat and expand. If the ground water is able to leach out any soluble salts from such strata, the rock will crumble and become liable to slide.

THE GOHNA LANDSLIP.—Perhaps the biggest of all known landslips was that which occurred at the end of the rainy season of 1893 in the valley of the Birahi Ganga near Gohna in British Garhwal ("The Gohna Landslip," *Rec. Geol. Surv. India*, Vol. XXVII, 1894, p. 55). The actual locality lies about 130 miles north of the Himalayan hill station of Naini Tal.

On entering the gorge of the Birahi Ganga, black carbonaceous and pyritous shales, dolomitic marls, pyritous dolomites, dolomitic limestones with chert, and small bands of talc and talc schists are met with. All these beds, whether shaley or dolomitic, are charged with pyrites. The decomposition products of this mineral reacting on the hydro-carbons of the carbonaceous shales have given rise to the sulphuretted hydrogen emitted by the springs below the village of Gohna.

A small slip had occurred on the slopes of the Maithana spur (11,109 feet high) in 1891. The cliff then appears to have had a surface slope of 54°. The rocks exposed in the cliff front, although crumpled and faulted in a complicated manner, dip towards the valley at an angle of from 45° to 50°—*i.e.* less steeply than the hill-slope—thereby giving a free outfall to the overlying mass on a dip surface.

On the 6th September, 1893, two falls took place, damming back the river to form the present lake. The landslide continued for three days, with deafening noise and clouds of dust which darkened the neighbourhood and fell for miles around, whitening the ground and tree branches like snow. Further slips occurred at subsequent intervals after heavy rain—blocks of several tons came bounding from ledge to ledge for more than 3,000 feet over the broken hill face with a low rumbling noise and clouds of dust.

In the first fall the hill-side evidently pitched forward and rested against the cliff of similar rocks on the opposite side of the valley nearly a mile away. The second main fall slipped down in a normal way, so that a saddle, 5,850 feet above sea level, was formed between the two masses of debris. The total volume of broken material stretched for two miles along the river valley to a depth of at least 850 feet at the saddle referred to above. A section along the valley from the down-stream side shows an upward slope from the bed of the river below Gohna to the saddle of 11½°, and from the saddle a down-slope

upstream of 10°. The old bed of the stream on this line had a declivity of about $2\frac{1}{2}$°.

The glacier-fed streams slowly filled this reservoir—it was estimated that the impounded waters would top the saddle by the middle of August, 1894. Fears were entertained that once the water overflowed, the dam would give way entirely, and that the floods which might follow would carry devastation down the Ganges valley to the plains of India beyond Hardwar.

The lake overflowed the dam early in the morning of the 25th August. The scouring action at the outflow was checked—as predicted by Sir Thomas Holland—by the reduction of the slope and by the exposure of large blocks of dolomite in the dam. However, a considerable discharge did take place, and the flood rose 140 feet above high flood level in places far down the valley.

The following remarks by an eminent American writer, William Morris Davis (see his "Physical Geography," pp. 181-183) are of interest in connection with this landslip:

"In the meantime the danger that the lake might burst out in a great flood being perceived by the British engineers in charge of the public works in India, the bridges in the lower valley were removed; safety marks were set up on the valley sides, 100 or 200 feet above ordinary river level, indicating the height above which the flood would probably not rise; and a telegraph line was constructed from the dam to Hardwar, to give prompt warning of the outburst.

"The flood occurred at midnight, 26th-27th August, 1894. In four hours about 400,000,000 cubic yards of water were discharged, cutting down the dam nearly 400 feet, flooding the valley to a depth of from 100 to 170 feet, and rushing forward with a velocity of 20 miles an hour. Many miles of valley road were washed away. Every vestige of habitation was destroyed in villages along the Ganges above Hardwar. But so well was the notice of danger given that only one man lost his life, and that because he would not heed the warning. Under a less intelligent control, thousands of people must have perished in such a catastrophe."

A permanent lake remains which is nearly three miles long, about a mile wide at its greatest width, and over 300 feet deep in places, although considerable silting is in progress.

Several causes can be traced as having conspired to the one end of bringing about the catastrophe. Among these the most important, because it gave facilities for the action of all the others, is the steep dip of strata towards the valley. The dip, 45° to 50°, was greater than the angle of repose of the strata (dolomite and shales), and owing to the angle of the surface (54°, due to undermining by the stream) being greater than the dip, there was a free outfall into the valley below.

In addition to the structural instability of the rocks, a series of minor causes assisted in (A) loosening the strata, or (B) otherwise impelling it down the slope. Of these minor causes the more important, in order, were:

(1) Dolomitization;
(2) Solution by atmospheric waters;
(3) Reduction of coefficient of friction by water;
(4) Expansion of products on oxidation and hydration;
(5) Changes of temperature, and
(6) Hydrostatic pressure.

(A) Loosening of the strata.

(1) Dolomitization. The change of ordinary limestone into dolomite (see *Rec. Geol. Surv. India*, Vol. XXVII, 1894, p. 58) is accompanied by an increase of specific gravity from about 2.73 to 2.83, and consequently a corresponding decrease in volume which results in joints and fissures. These planes of weakness offer facilities for increased removal of material by solution, or the introduction of minerals like iron pyrites.

(2) Solution by atmospheric waters. Besides the mere solution along joint and bedding planes, minerals like iron pyrites become decomposed and the products of oxidation and hydration act as solvents for the production, from dolomite, of sulphates of lime and magnesia, which are ultimately carried away in solution. (See *Rec. Geol. Surv. India*, Vol. XXIII, 1890, p. 220.)

(3) Reduction of coefficient of friction by water. When it is remembered that ϕ for *damp* clay may be as high as 45°, whereas that for *wet* clay is as low as 14° (see table given on page 172), it is evident that the effect of water on a soft bed of shale is equivalent to lubrication. (See *Rec. Geol. Surv. India*, Vol. XIII, 1880, p. 277.)

(B) Subsequent changes impelling strata in the direction of least resistance.

(4) Expansion of products on oxidation and hydration. The sulphuric acid produced by the oxidation of the pyrites would decompose the carbonates of lime and magnesia and form partially hydrated sulphates, which would expand subsequently on more complete hydration before final removal. This action taking place in small cracks would give rise to the production of a number of wedges which would dislocate the rocks (see *Rec. Geol. Surv. India*, Vol. XXIII, 1890, p. 221).

(5) Changes of temperature. The expansion caused by the diurnal variation in temperature, particularly in summer, and the frost action

in winter, would result in the development of the phenomenon known as " creep."

(6) Hydrostatic pressure. There was every facility for the rain water to sink into the steeply inclined strata and to exert a considerable hydrostatic pressure at the lower zones of the slip face, thus adding to the weight of the material capable of sliding.

THE PRESSURE OF CLIFFS.—Most engineers who have constructed causeways or embankments across boggy ground have probably had experience of " swells " which have appeared on one or both sides of the embankment as a result of the pressure exerted on the soft material by the weight of the earthwork. It is therefore a matter of no surprise to these engineers to expect a similar pressure to

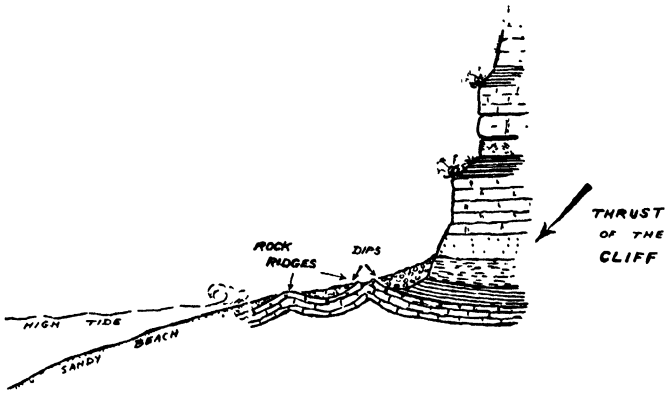


FIG. 26.
Pressure of cliffs.

be existent at the foot of a steep cliff (Fig. 26). If the rocks at the foot of such a cliff consist of soft horizontally-bedded material, such as alternations of clay and limestone, evidence of this pressure may be detected by the presence of a " bulge " or " ridge " in front of, and at a short distance from, the foot of the cliff. Occasionally the actual ridge is not evident, owing to erosion by the sea waves and tidal currents, but a close examination will often show that there is an inward dip of the strata in the base of the cliff and an outward dip of the beds a little distance away.

On such a foreshore it would be very unwise to erect heavy masonry sea-walls for protective purposes, as they would be buckled and broken by the pressure exerted by the thrusting mass of the cliff. Groynes are more flexible for this type of protective work. The best protection here, as elsewhere along shores, is a bank of shingle forming a storm beach. The weight of this bank of shingle, moreover, counteracts in some measure the weight of the cliff. This buckling of the foreshore in front of great cliffs is not confined to the immediate vicinity of the

cliff base, but may be felt at some distance from it. There may be, in fact, a series of parallel ridges seaward from the cliff, or there may be a corrugated structure of the strata along the foreshore with axes parallel to the cliff. In each case the weight of the cliff is usually the cause of these phenomena.

The bulging of the lower slopes of a hill-side may also be due to this phenomenon, and not merely to the subsoil "creep" which is so evident on many slopes of loose material. The phenomenon is also of common occurrence in coal mines, and it often happens that the roof or floor of a "roadway" bulges inward and has to be ripped or bated to keep the passage open.

SAND DUNES.—Few people have escaped the annoyance caused by dust storms, and it is interesting to know the size of sand grains carried by a light breeze.* The following results were obtained by J. A. Udden (*Jour. Geol.*, Vol. II, 1894, p. 323) by throwing coarse loam sand into a wind of 8 miles an hour.

Average dia. of particles.	Deviation of sand particles.
0.75 millimetres	Described a path diverging about 10° from a vertical line.
0.37 „	Deflection about 45° from a vertical line.
0.18 „	Driven almost horizontally.
0.08 „	Suspended in air for a considerable distance.
0.04 „	Apparently completely wind-borne.

Smaller particles were completely wind-borne.

This experiment shows well the sifting power of the wind.

Professor Flinders Petrie (*Pro. Roy. Geographical Soc.*, 1889, p. 648) has estimated that, roughly, 8 feet of soil has been removed from the surface of the ground in some parts of the Nile delta during the last 2,600 years. This blowing forward of dry loose soil and sand is common in desert areas and along coasts with wide sandy shores which are subject to strong prevailing winds. The accumulation of masses of shifting, loose sands, owing to the presence of irregularities of the ground or other obstacles, results in the formation of the sand dunes which are so familiar to most people. In desert regions such sand dunes may not be troublesome, but in some cases they have covered important oases, and thus rendered journeys either dangerous or impossible. In more inhabited places sand dunes are invariably a nuisance; buildings have been overwhelmed, towns rendered uninhabitable, streams choked up, or the drainage deflected.

* Slight breeze	1 to 10 miles an hour.	Gale	40 to 60 miles an hour.
Light breeze	10 to 20 „ „ „	Strong gale	60 to 80 „ „ „
Strong breeze	20 to 40 „ „ „	Hurrican	upwards of 80 „ „ „

The shapes of most sand hills take a crescent form, with the convex side to windward, with a steep slope in the cusp (see Fig. 27).

Some of these sand dunes may attain a height of over 250 feet, and if not fixed, are ceaselessly moving forward under the blowing action of the wind—the coarse particles being left at the windward toe, while the fine material trickles down the steep declivity in the cusp.

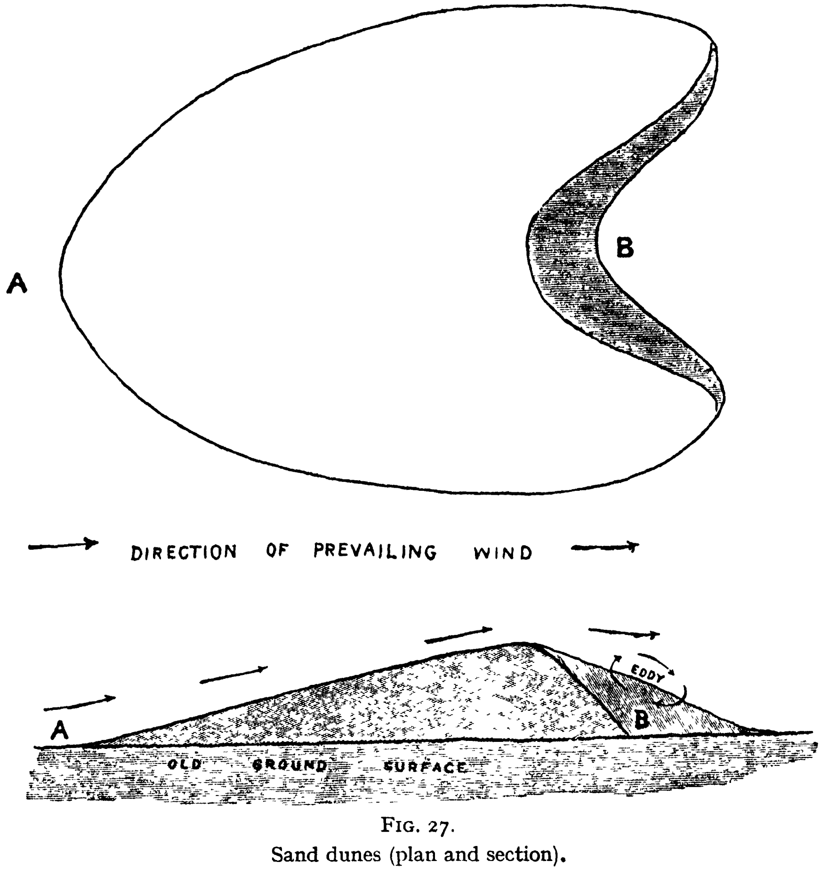


FIG. 27.
Sand dunes (plan and section).

The management of sand dunes has been a pressing question in various countries, and minutely studied by several engineers (see *Handbuch des deutschen Dünenbaues*, by Paul Gerhadt, Johannes Abromeit, Paul Bock, and Alfred Jentzsch: published by order of the Prussian Ministry of Public Works: Berlin, 1900).

The principle underlying the management of sand hills, *i.e.* the way to fix, to prevent, or, where desirable, to cause the formation of sand dunes, is in all cases the same whatever may be the detailed mode of application.

"It consists in the setting up of obstacles which will break the force of the wind and prevent scouring of the loose sand, while

causing a deposit of that which is blown along, or near, the surface, by the wind." (See R. D. Oldham, *Mem. Geol. Surv. India*, Vol. XXXIV, Part III, 1903, p. 153.)

" A solid obstacle, such as a wall or plank fence, causes a certain check in the wind currents, and sand is deposited in front of the wall, but not in its immediate vicinity. Here a strong eddy is formed and not only is no sand deposited, but there may even be scour as indicated in Fig. 28, and it is only when the heap of sand in front of

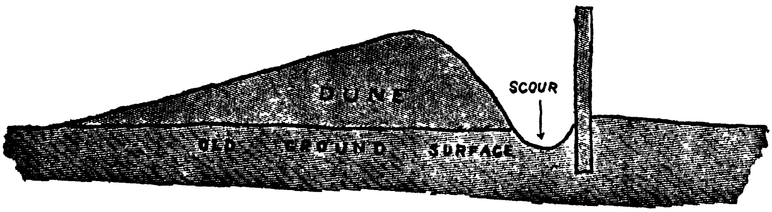


FIG. 28.
Obstacle to sand dunes (inadequate).

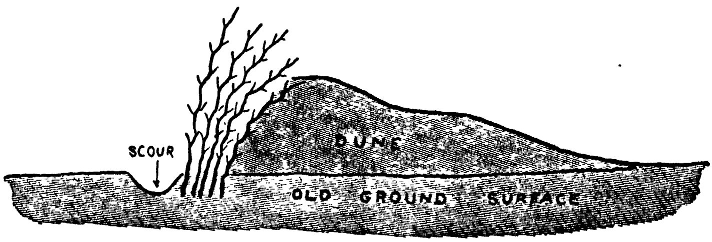


FIG. 29.
Protection from sand dune (fair).

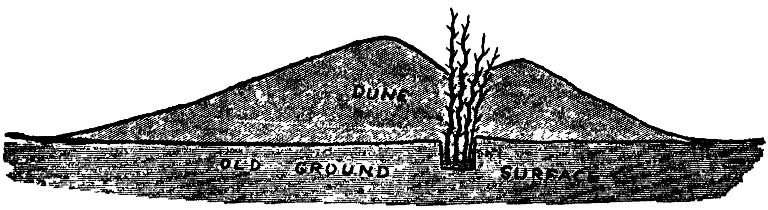


FIG. 30.
Sand dune (stop).

the wall gradually rises to a greater height than it, that this hollow fills up, and the wall is completely buried in sand.

" The effect of an isolated, flexible, permeable obstacle, such as a clump of grass, is different ; here the resistance to the wind is much less, there is no heap formed in front, nor any great scour. On the other hand, the wind which filters through the grass stems has its velocity reduced and sand is deposited behind the grass clump ; as shown in Fig. 29.

" The effect of a rigid and permeable obstacle, such as an open fence, is a combination of the two; in front no eddy is formed, there is no scour, and the check in the velocity of the wind causes a deposit of sand both in front and behind the obstacle as indicated in Fig. 30.

" The mode of application, size, and distribution of the fences depend on the object to be attained. Where it is merely desired to fix loose moving sand, it has been found best to cover the surface with a network of low fences formed of twigs some 20 inches in length, of which about 8 inches are buried and 12 inches stand above the ground. Planked in rows at right angles to each other and 4 yards apart, it is said that even strong breezes will blow harmlessly over the loose sand."

CHAPTER X

QUARRYING AND TUNNELLING

QUARRYING and mining are intimately connected with each other. In the former, the workings are open to the sky; in the latter, the operations require overhead protection.

QUARRYING IN LOOSE GROUND.—The location and opening up of a quarry often necessitates some exploratory work, as it is not always possible to see the unweathered or jointed nature of the rock.

The fundamental principle of quarrying is to arrange the working face in such a way that the rock can be easily freed with the least expenditure of energy, and when free will slide forward under its own weight. In other words, quarrying aims at producing landslips for a useful purpose. If the material required is loose, incoherent gravel, it is usually necessary to keep the face of the quarry steeper than the angle of repose of the material. If the material consists of shattered rock which occasionally stands vertical, it may be necessary to undercut or blast it to enable the material to collapse into the quarry.

QUARRYING STRATIFIED ROCK.—The same strategy is used in extracting blocks from bedded rocks. It is known that most hard rocks have three divisional planes which are usually at right angles to each other. In Photograph XIII the beds of sandstone are seen to be nearly horizontal; the bedding plane functions as one divisional plane, while the two sets of joints A and B function as the other divisional planes; with a little skill it is possible to detach blocks of various sizes; much, however, depends on the spacing of these joint planes. In slates the spacing of one set of divisional planes may be so close as to warrant the use of the name cleavage in designating them. Photograph XIV shows a slate quarry. In this case the bedding plane (b.p.), although inclined, is indistinct, while three distinct joint planes, A, B, and C—one nearly horizontal—are present. In neither of these cases is there a tendency for the liberated materials to slide clear.

It is, however, common experience to find one of the divisional planes, either the bedding plane or a joint plane, in an inclined position;

when this occurs, the blocks or slabs slide forward when they are freed from the main mass of rock. Fig. 31 shows a sandstone quarry in which the beds are tilted. The bedding planes are well separated, the strike joints are distinct, and the dip joints are less well developed. In this case the rock is first freed by a deep cutting parallel to the dip joints, while the working face has been cleared on the dip side parallel to the strike joint planes. By careful wedging, with perhaps a little

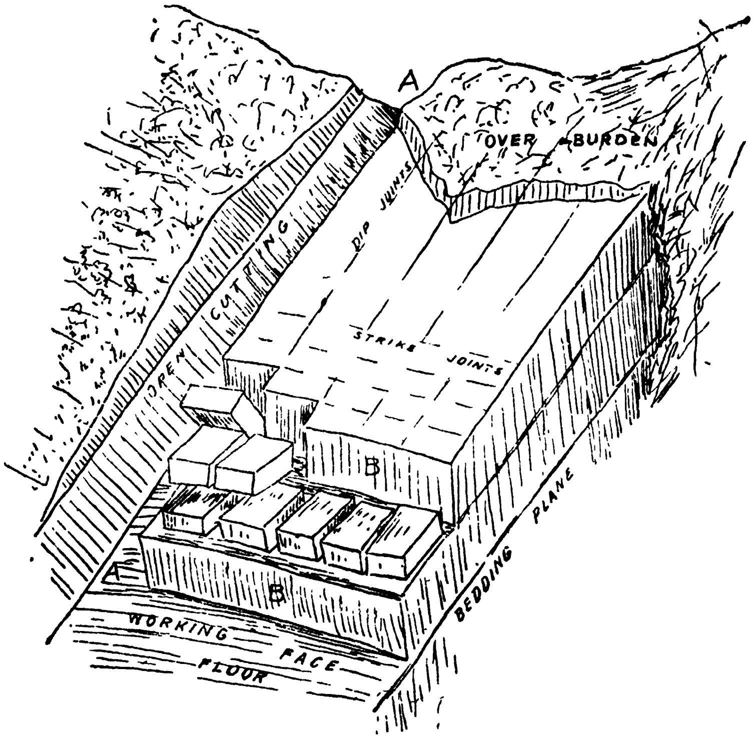


FIG. 31.
Sandstone quarry.

blasting and undercutting, the separate blocks can be easily prized off the working face.

Occasionally, the joint planes intersect each other at angles other than right angles. An example of this kind is shown in Fig. 32. Here a slate quarry is depicted with diagonal jointing and an inclined bedding plane. One of the two divisional planes—the cleavage—is perfect, while the other is less distinct. To work this rock, the working side is made on the dip side. Narrow side cuts, A-A, are made into the rock along the indistinct joint planes, and the slate is prized off along the cleavage planes.

In Fig. 33 steeply-dipping beds of marble are shown; they are depicted with irregular, but distinct, joints. The workman takes

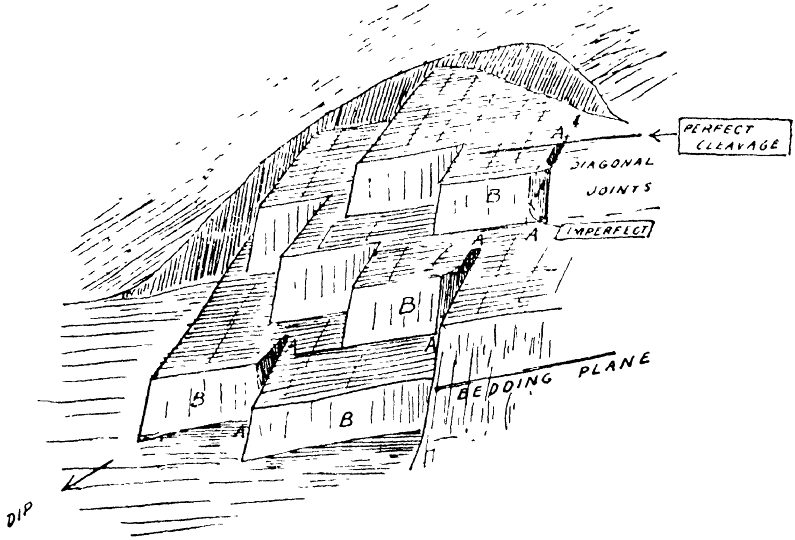


FIG 32
Slate quarry.

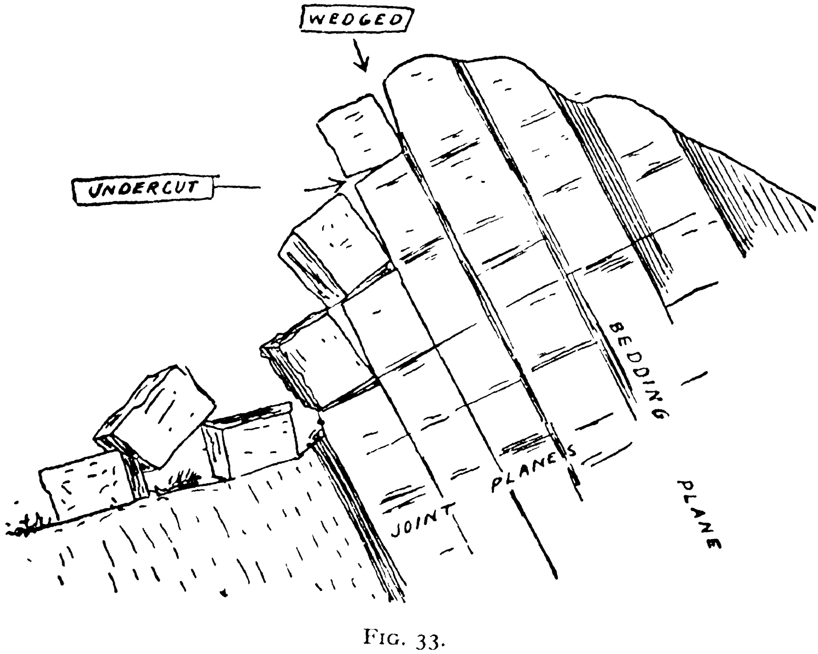


FIG. 33.
Outcrop of marble band.

advantage of these natural features to wedge and prize up the blocks and assist them to slide forward on the joint planes.

In more massive rocks, such as granites, etc., the joints may be far apart; consequently, it may be possible to quarry blocks of great size. Blasting is generally necessary in these cases, and the handling of the blocks may involve the use of elaborate appliances. The underlying principles, however, remain the same, *i.e.* to free the blocks along easily separable planes and to simulate the condition of weights on an inclined plane. If this is done, the cost of the work is very considerably reduced.

In opening up a slate quarry in West Australia, it was found that the slabs obtained varied from 1 to 3 inches in thickness. The dip of the beds was 20° to E. 30° S., the strike of the main cleavage was E. 12° S., with a southward dip of 48°.

When the armies had settled down to trench warfare it was discovered that most of the regular quarries for building stone and road metal lay behind the German lines. Quarries were opened in the carboniferous and devonian limestone out-crops near Marquise, midway between Calais and Boulogne. Most of this material was used as road metal with tar, and some of it was used in the construction of concrete structures—" pill-boxes," etc. (See " Quarrying Operations of the British Army in France," *The Quarry*, etc., Vol. XXV, 1920, p. 83, also other valuable papers on this subject, *e.g.* " Portland Stone Quarries," by Jenkyn Griffiths, *The Quarry*, Vol. XXVI, June, 1921, p. 217; also " The De Lank Quarries," *The Quarry*, Vol. XXVI, February, 1921, p. 44; also " The Aberdeen Industry," by John Adam, *The Quarry*, Vol. XIX, 1914, pp. 173, 201, 229, etc.)

SIZES OF BLOCKS QUARRIED—GRANITE.—The following examples of the use of large granite blocks for monuments and buildings are of interest. Perhaps the greatest blocks of stone are those at Baalbeck and the quarries of that ancient Syrian town.

(1) A large obelisk is that in the piazza of St. John Lateran at Rome. It was brought by Constantine from Heliopolis. The dimensions are 105′ 9″×9′ 10″×9′ 8″. Its probable weight is 800 tons.
(2) Cleopatra's Needle (syenite) is 68′ 5″ high and weighs 186 tons.
(3) A monolith of shap granite, 25′ 3″×3′ 2″ square, weighing 22 tons, has been erected as a War Memorial at Leighton Buzzard.
(4) Nelson's Monument is made of Dartmoor granite.
(5) The Eddystone Lighthouse has been built of Cornish granite from the De Lank quarries, Bodmin Moor.

(6) The Nurse Cavell Monument, St. Martin's-in-the-Fields, was manufactured at the De Lank quarries. This Cornish granite weighs 165 lbs. per cubic foot.
(7) The plinth of Buckingham Palace is also of Cornish granite.
(8) The grey granite base of Queen Victoria's Statue, in front of Buckingham Palace, is of Scotch granite from the neighbourhood of Aberdeen.
(9) The polished stone posts round the terraced front of St. Paul's Cathedral are of shap granite.
(10) The sarcophagus of the Duke of Wellington in St. Paul's Cathedral is of a peculiar tourmaline granite from Luxullian, St. Austell, Cornwall.
(11) In addition to the use of granite as a building stone, it is to be remembered that large quantities of this stone are used for kerbs, steps, pavements, etc.
(12) The docks at Bombay are built of granite from the De Lank quarries, Bodmin Moor, Cornwall. (See *The Quarry*, etc., Vol. XXVI, 1921, p. 45.)

MARBLE.—the following extracts from " The Stones of London," *The Quarry*, Vol. XXVII, 1922, p. 48, show the importance attached to the use of white marble of good quality.

" The great modern example of monumental white marble is, of course, the Queen Victoria Memorial, the work of Sir Thomas Brock, R.A., opposite Buckingham Palace. It is of interest to note the quantity of marble needed for a monument of these dimensions. In the lower part of the Memorial, that is, in the fountain basins, retaining walls, pedestals, etc., 1,000 tons of selected Sicilian marble were employed. Great care was exercised in the selection of all marble employed; 3,000 tons came from Italy for the purpose, of which 1,500 were rejected and some 2,300 tons actually embodied in the Memorial. The throned figure of the Queen, 13 feet high from footstool to crown, is carved from a single block. The original block for the group symbolising Truth, on the south side, weighed 40 tons, the rough trimming before the final carving reduced it to 25 tons. These figures give an idea of the amount of waste in works of this kind."

MAGNESIUM LIMESTONE.—After an exhaustive enquiry (in 1839), magnesium limestone from the Auston quarries was utilised for the building of the Houses of Parliament. As seen to-day, the selection of this stone was unfortunate. The stone has suffered greatly from the acid fumes in the atmosphere of London. However, the selection was evidently influenced by the fact that similar stone had been used in Southwell Minster and had weathered very well. In this connection

Per favour D. G. S. I.] SANDSTONE (PAVING FLAGS) QUARRY. [*Photo by H. C. Jones, Esq.*

The well-bedded fine grained sandstone lies horizontal and can be cleared along the bedding plane. The stone is traversed by two sets of vertical joints at right angles.

BARO QUARRY, GWALIOR.

[*To face page* **194.**

Per favour D. G. S. I.]

TYPICAL SLATE QUARRY.

[*Photo by Sir Thomas Holland.*

The original bedding plane of strata b-p. A is the main cleavage plane. B is the line of vertical jointing. C is the plane of horizontal jointing.

MONGHYR QUARRIES, BENGAL.

[*To face page* 195.

the following remarks are of value, because they show how much caution is necessary not only in ascertaining the exact locality from which an obviously good stone has been obtained, but also in locating the right bed from which it was extracted.

"It was found afterwards that the Bolsover Moor stone had not been used in Southwell Minster at all, the stone for this edifice having been got from Mansfield Woodhouse. Also it was found that neither at Bolsover Moor nor at Mansfield Woodhouse could blocks of sufficient size be obtained. Therefore it was necessary to procure the stone from the Auston quarries as being the nearest substitute for the kind actually selected. A little of the Mansfield Woodhouse stone, amounting to about 20,000 cubic feet, was indeed used at Westminster, and has since been found to have worn well, but the greater part of the structure was executed in Auston stone.

"Now we come to an important part of the question. The Auston quarries, from which 200,000 cubic feet of stone were taken for this purpose, were worked indiscriminately from the surface to the bottom of the formation to a depth of 35 feet, the stone lying in 17 beds varying in thickness from 4 feet to a few inches. Although most of the stone was of good quality, there were some beds of a softer nature; yet the whole of the beds were used, no particular beds were followed horizontally, no supervision at the quarries was provided for, and no seasoning of the stone took place. The stone was sent to London within a fortnight of quarrying, even throughout the winter. So little stone was rejected at the quarries that almost the only waste was that derived from cutting the blocks.

"It is thus perfectly clear that the Commissioners' choice was not so much at fault as the supervision of the quarrying and selection of the stone." ("The Stones of London," by J. V. Elsdon and J. A. Howe, *The Quarry*, Vol. XXVI, 1921, p. 349.)

SANDSTONE.—Sandstone is used very largely in important buildings. Much depends on the thickness of the layers. In the case of small blocks there is seldom much subsequent trouble if the stone is compact and the pore-spaces are filled with a matrix of calcium carbonate, or silica, or iron oxide. If the rock is very porous, the face of the stone-work is liable to scale as a result of frost action. With large blocks, however, it should be recognised that nearly all sandstones, no matter how compact they may appear to the eye, possess in some degree the tendency to develop planes of weakness parallel to the bedding. As examples of the use of massive sandstones, mention may be made of the terrace at Trafalgar Square and the Thames Embankment. In both these cases the stone was Millstone grit of carboniferous age. In the former case the rock was obtained from the old Craigleith sandstone quarry near Edinburgh. Single blocks, $136' \times 20' \times 8'$, weighing 1,500 tons, are said to have been extracted in 1823 from these workings. Some of this sandstone was used in

building Buckingham Palace. In the latter case (Thames Embankment), the stone was obtained from quarries near Ruabon.

CUTTINGS.—As regards cuttings, G. W. Macgeorge ("Ways and Works in India," 1904, p. 257) says:

"The principal difficulties met with in heavy cuttings are due to the nature and inclination of the strata cut through, the behaviour of the material under the influence of exposure to weather, and the presence of springs. Some materials will not be secure from all danger of slipping at almost any angle of slope, and the heavy expense of retaining walls may have to be resorted to. Other materials require very flat slopes and expensive drainage-works before stability can be secured. Alternate strata of sand and clay, or shale, are especially dangerous or troublesome, particularly if heavily inclined and full of water. Other materials stand firmly at slopes of 1½ or 2 to 1. Hard clean rocky strata, although expensive to cut through in the first instance, are often the most economical in the long run as the slope will stand almost vertical, imposing a smaller quantity of initial excavation, and little or no subsequent outlay. . . .

"The cost of cuttings increases in proportion to their depth, hence there is always a certain limit at which it becomes more economical to burrow, or tunnel underground, than to continue the open cutting. This limit, although it will vary somewhat according to the nature of the material to be excavated, is in ordinary cases found to lie somewhere between 60 or 70 feet of depth. In very hilly or mountainous country—unless it so happens that a very great deal of material is required for high embankments, which cannot be obtained except from the cuttings—this economical depth is soon reached, and tunnelling will be resorted to with more or less frequency. Short tunnels commonly present little difficulty, and can be bored or 'driven' through a hill from end to end without intermediate shafts. Beyond a certain length, however, and in cases where the depth of the tunnel below the natural surface of the ground is moderate, it becomes economical to sink one or more shafts, or wells, along the centre line of the tunnel, from the bottom of which boring or driving the tunnel can be carried on in two directions. By this means the work is prosecuted with greater rapidity from more numerous points of departure.

"Simple tunnelling through hard rocky materials is generally carried on by blasting, either by gunpowder, dynamite or other explosive. A small opening or 'heading' is first pierced by miners working in front, and others following them gradually enlarge the opening to the full section of the tunnel. In the softer kinds of material, however, the difficulty and expense of tunnelling is often greatly increased, especially if considerable quantities of water are met with. The whole of the sides and roof of the tunnel excavation as it advances will be shored up, or supported by temporary timber work, and a permanent lining of stone or brick masonry of a strength sufficient to withstand the pressure of the surrounding material will be necessary, every part of which will be set in durable cement, to prevent the percolation of water. Very heavy and expensive pumping operations may also be necessary."

MINING.—When a working is carried underground and the overlying rock forms a roof, the operation is termed mining, as previously stated. The excavations of great chambers which result from the removal of rock salt in the workings at Khewra in the Salt Range of the Punjab ; the removal of slate from inside a hill, as in some of the North Wales localities ; the extraction of coal by the " Board and Pillar System " for seams greater than 5 feet or by the " Longwell Method " in the case of thinner seams, as carried out in the coalfields of England and elsewhere ; the removal of mineralised rock or vein matter from an ore-body by systemmatically cutting out stopes, as in the gold mines of the Rand ; the driving of " tunnels " or " headings " in warfare for the purpose of blowing up enemy forts or trenches, etc., are all forms of mining. The details of the methods employed in these several operations lie outside the scope of this book. We are here only concerned with the geological factors which influence the most economical methods for attaining the object in view. The massiveness and toughness of the rocks or their decomposed or unconsolidated condition ; the horizontality and continuity of bedded rocks ; the folded or faulted structure of the strata ; the presence of large volumes of water ; the possible dangers from noxious gases or earthquakes shocks, etc., are aspects upon which geological knowledge may throw considerable light. Questions involving the ease or otherwise with which two dissimilar kinds of rock, whether massive or bedded, are separable along their plane of contact, can only be answered by actual exploration of the junction. This is often a matter of importance, as it involves many of the factors mentioned above, *i.e.* danger from inrushes of water, size of galleries which can be safely excavated, the amount of timbering which may be necessary, and the likelihood of falls of roof in certain kinds of strata. In a coal mine, if the seam is easily parted from the overlying rock of the roof and from the underlying stratum which forms the floor of the working, the whole thickness of the seam can be removed. If the bedding planes of a roof consisting of thinly-bedded shales and sandstones do not adhere strongly, or these rocks are soft and and damp, they may bulge into the workings by the weight of the superincumbent strata. Similarly, this weight pressing on the sides of a working in a coal seam on soft clay may cause the floor to push up into the working. Instances occur where certain bedded and folded rocks, instead of being found in a crushed condition due to the tectonic forces which caused the buckling, are not greatly fractured but have become like a pile of thin plates, the hard layers having slipped one over the other. In such cases a very difficult problem might have to be faced if these slabs begin to slide into a working.

MINING GENTLY-INCLINED BEDS.—In mining gently-inclined seams of coal, it is usual to find the bedding planes of the floor and roof parallel and sufficiently distinct to allow of easy separation, both above and below. The " roads " or drivages are usually made down the dip and connected by cross-drivages on the level (i.e. parallel to the strike), because in most cases there is a well-developed system of strike joints which are technically called the " cleat " of the coal. Then, starting at one or both ends of the level drivage, the coal is prized off the seam on the upper side; it falls forward into the level and is loaded and hauled away. In many cases the coal has to be " holed " below or undercut; in some cases the cutting has to be made above to free it from the roof. Blasting facilitates the work of prizing off the face.

If a seam of fire-clay is being worked, joints may not be sufficiently well developed, and the material will have to be undercut and then blasted.

Conditions often arise when this ideal method cannot be followed. In these cases, the miner must use his common sense and take advantage of existing natural features.

MINING STEEPLY-INCLINED BEDS.—Where a bed or mineral vein is nearly vertical, the best plan is to make drivages (levels), one below the other, vertically at intervals. These are then connected with each other by a single shaft or by winzes. The rock may then be attacked in three ways: (1) The roof of each level may be directly attacked and the material allowed to fall in—this is known as underhand stoping; (2) the floor of the level may be attacked and the material dropped down the winze into the level below—this is overhand stoping; (3) an intermediate level may be driven and the material attacked either by overhand or underhand stoping and the debris allowed to fall through subsidiary winzes, or hoppers, into the level below. Local conditions may, however, necessitate modifications, and the miner must then do the best he can under the circumstances.

WORKING IN LOOSE MATERIAL.—In these cases the training of the mining engineer should help him to meet the conditions of the particular difficulties which present themselves. Shaft-sinking, erection of caissons, tunnelling, etc., in water-bearing gravels or running ground are as familiar to the civil engineer as to the mining man. The failures and accidents which occasionally take place in these operations are usually the result of underestimating the hydrostatic pressure of the fluid or the semi-fluid material. This is normally calculated as twice that of water under the same " head." Actual mining in wet, loose, sandy ground is a dangerous proceeding, and

it is very improbable, owing to the elaborate protection, etc., which is necessary, that such an operation would be attempted. It might be worked by dredging. The working of gold-bearing placer-gravels under a strong massive sheet of lava, such as the alluvial *deep-leads* of California, Victoria, and New South Wales (see J. Park, " A Text Book of Mining Geology," 1911, pp. 33-37), is a different matter. It would ultimately pivot on the capacity of the pumps to keep the workings unwatered. The support of the roof would not then give rise to apprehension.

SUBSIDENCE DUE TO MINING.—Mining operations, directed for the purpose of winning mineral wealth from the earth, are outside

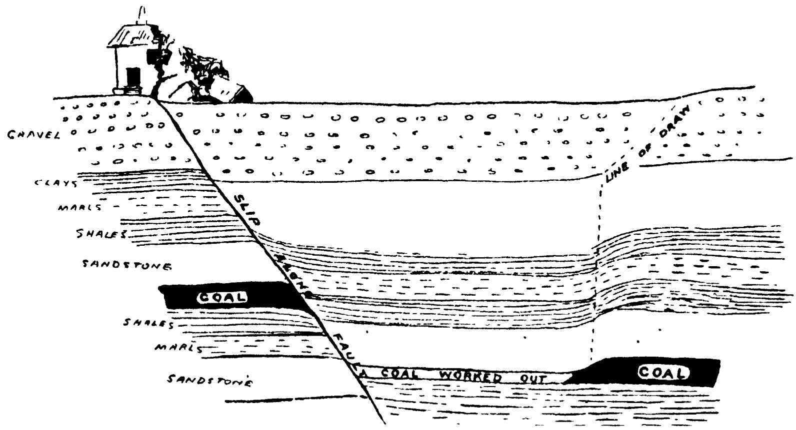


FIG. 34.
Subsidence due to mining.

the province of the civil engineer. It is true that tunnels and shafts come under the term mining, but these works are in the nature of preliminary approaches to the actual extraction of mineral wealth.

The civil engineer is, however, concerned with certain results which follow extensive mining. The most important of these is that of the subsidence of the surface above underground workings. Such subsidence may damage tunnels, railway lines, canals, bridges, important buildings, seriously affect reservoir basins, dams, roads, water and gas mains, and so interfere with the surface drainage as to cause lakes and marshes to form in otherwise well-drained areas, and ultimately alter the healthiness of the district. (Fig. 34.)

As Dr. Sherlock says (see " Man as a Geological Agent," 1922, p. 127):

" The study of subsidence due to mining is still in an unsatisfactory condition. Professor Galloway (see ' Subsidence caused by Workings in Mines,' by W. Galloway, *Proc. S. Wales Inst. of England*, Vol. XX, 1897) has given an excellent account of the investigation carried out by Fayol, at Commentary in France, on the distance and

direction in which the effects of subsidence due to coal extend. Subsidence is felt for a certain distance above the excavation, but may not extent up to the surface. The area affected forms an ellipsoidal block cut off below by the excavation. If this lies horizontally, the ellipsoid is symmetrical about a vertical plane through the middle of the excavation, but if as is usually the case, the coal-seam was inclined, then the ellipsoid is unsymmetrical (see Fig. 35).

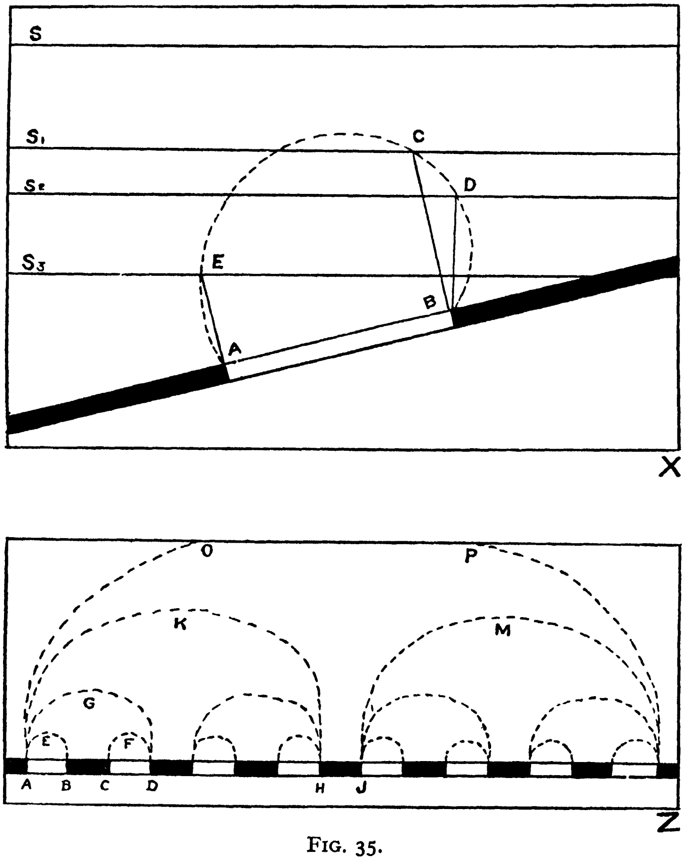


FIG. 35.
Fayol's diagrams.

"In Fig. 35 if AB represents the excavations in an inclined coal-seam, ABC a vertical section of the block of strata affected by subsidence, and S_3 is the surface of the ground, then the line AE, passing through A and the point where the ellipse cuts the surface, will be practically perpendicular to AB, when the excavation is not far below the ground, and E marks the limit of the subsidence. If the excavation is at a greater depth, so that S_2 represents the surface level, then the line BD corresponding to it as AE did to S_3 may be vertically above B. If SS is the surface, the ellipsoid is cut at C where BC is perpendicular to AB. Finally, at a still greater depth, the surface level S may not cut the ellipse at all and there will be no subsidence.

"The effect of pillars in supporting the roof of a mine is shown in Fig. 35. If AB, CD are the parts excavated, and BC is a pillar, the subsiding blocks are shown in section as ABE, CDF. When the pillar is removed the block ADG subsides. When the pillar HJ is left, the subsidiary blocks are AHK and JLM. When the whole seam from A to L has been removed the subsiding block is ALPO." In the last case the ground between O and P would subside.

Subsidence is partly prevented by careful packing of the waste stone into the excavations (gob). The following table (after Fayol) gives the results of experiments to find the amount of compression of crushed materials.

Rock	Space occupied by broken or crushed rock under a pressure of—			
	100 kg. per sq cm	200 kg. per sq. cm	500 kg per sq. cm	1000 kg per sq cm
Clay	100	90	75	70
Shale	128	116	110	97
Sandstone ..	130	125	120	105
Coal	130	125	118	109

Space occupied before being broken, 100 in each case. 100 kg. per sq. cm. = 1,422 lbs. per sq. inch.

A pressure of 100 kg. per sq. cm. corresponds to a depth of 500 metres 200 kg. per sq. cm. to 1,000 metres, etc. Sandstone and shale, when crushed, occupy a volume about 60 per cent. more than before crushing.

Stock and Young have compiled the following information in this connection.

Depth in feet	Percentage subsidence	Thickness of material removed	Locality	Authority	Filling
360	70	5.0	England	S. R. Kay	
990	64	3.5	,,	,,	
650	68	5.5	,,	Dixon	
748	19	7.5	France	Fayol	Stowing
2600	0	13	,,	,,	Harmless depth without stowing
1040	0	13	,,	,,	,,
390	40	7	England	Gresley	33% of seam in gob.
1500	30	5	,,	Hay	Packing

These results indicate that there is generally some subsidence even with elaborate stowing, less at great depths than in shallow mines.

Subsidence Caused by Pumping.—It was at one time feared that the large volumes of water which are obtained from the porous water-bearing horizons under London would result in surface subsidence, but it is now appreciated that wherever the interstitial water is obtained without removing the rock material in solution, the strata will not subside. On the other hand, the method of salt working, by pumping brine, has caused serious subsidence in various parts of Cheshire and elsewhere in England.

The occurrence of faults must be carefully noted as, where they cross the area affected, the lines of subsidence are deflected and pass along them. Being planes of fracture, movements may be transmitted by them to considerable distances.

When the regular beds are covered with a thick layer of soft, loose, sandy material, especially if it is water-logged, the movement has a tendency to expand outward, owing to the beds sinking along the angle of repose (Fig. 42).

"The Theory of Subsidence," by Henry Louis (see *Colliery Guardian*, Vol. CXXIV, pp. 1215 and 1276), is an important paper.

The discussion which followed this paper shows that Professor Henry Louis had not satisfied mining men that a satisfactory formula had been found for calculating the angle of "draw." The value given, *i.e.* 26° 35′, was subject to various modifications, such as the kind of strata involved—unconsolidated or consolidated, laminated or in massive beds, horizontal or tilted.

In this connection an interesting paper may be quoted. A distinct earthquake was felt in the Glasgow district on the 14th December, 1910. Dr. Davidson, the seismologist, after an examination of the facts, decided that it was due to the collapse of the overlying strata into the old workings of a local mine. The severity of the shock, *i.e.* 5.5 Rossi Forel scale (moderate to strong), was taken as evidence of the shallow depth of the focus of the shock. Professor J. W. Gregory (see *Colliery Guardian*, Vol. CI, 1911, pp. 319 and 836), while admitting that earthquakes are seldom known to affect the workings of mines, whereas this particular shock was very noticeable in the colliery workings of the district, disagrees with the conclusions arrived at by Davidson. He considers that this was a normal earthquake shock, probably caused by the slipping of strata along a fault plane, and that its focus was far deeper than 2,000 feet—the estimated depth of the old workings.

Professor W. G. Fearnsides (see *Colliery Guardian*, Vol. CXI, 1916),

These results indicate that there is generally some subsidence even with elaborate stowing, less at great depths than in shallow mines.

Subsidence Caused by Pumping.—It was at one time feared that the large volumes of water which are obtained from the porous water-bearing horizons under London would result in surface subsidence, but it is now appreciated that wherever the interstitial water is obtained without removing the rock material in solution, the strata will not subside. On the other hand, the method of salt working, by pumping brine, has caused serious subsidence in various parts of Cheshire and elsewhere in England.

The occurrence of faults must be carefully noted as, where they cross the area affected, the lines of subsidence are deflected and pass along them. Being planes of fracture, movements may be transmitted by them to considerable distances.

When the regular beds are covered with a thick layer of soft, loose, sandy material, especially if it is water-logged, the movement has a tendency to expand outward, owing to the beds sinking along the angle of repose (Fig. 42).

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Professor W. G. Fearnsides (see *Colliery Guardian*, Vol. CXI, 1916),

PHOTOGRAPH XV.

Per favour D. G. S. I.] SUBSIDENCE DUE TO MINING. [*Photo by Dr. C. S. Fox.*

The road from the right is closed and a diversion has been made round the left. A subsidence of nearly eight feet has occurred as a result of removing the pillars in a coal seam about 100 feet below.

KIRKEND CORNER, JHARIA COALFIELD.

[*To face page* 202.

in an elaborate paper, discusses "Some Effects of Earth Movement on the Coal Measures of the Sheffield District."

ADITS.—An adit is a blind tunnel. It has only one entrance, and may be driven into the side of a hill for drainage or ventilation purposes, or for working a mineral lode on that particular level in a mine. As a rule the alignment of an adit is determined by circumstances such as the configuration of the ground surface, the location of the workings to be drained, or the deposit to be worked. There is seldom much choice of direction. Cost, *i.e.* length of drivage in unprofitable ground, is naturally the factor which is mainly considered. It is usually the aim of the mining engineer to drive in the mineral-carrying part of the ground whether this happens to be a coal seam or a mineralised vein. Thus it is seen that the "strike" of the bed or vein usually fixes the direction. In a drainage or ventilation scheme it is the softness of the rock and its ability to stand without support that influence the alignment. A knowledge of the structure and condition of the rocks to be cut through is therefore essential. In the case of coal or metalliferous deposits, much information will probably be available from previous prospecting or mining in a particular locality. With a simple engineering scheme a preliminary geological examination may be necessary. However, this aspect of the subject will be found discussed in the next section under "tunnels."

INCLINES are adits driven at an appreciable slope, *e.g.* into an outcropping coal seam, etc.

TUNNELS.—The location of a tunnel, like the site of a bridge, does not often allow of much freedom of choice. A tunnel either becomes necessary at a given place in order to maintain an alignment through a mountain range or the spur of a ridge, or it is an advantageous alternative, in avoiding hilly obstacles, to an otherwise long or difficult detour.

In the construction of railways, roads, or canals, it is generally cheaper to drive a tunnel rather than make a cutting more than 60 feet deep, unless the excavated material is required for neighbouring embankments. It is true that in materials of rigid and unyielding character, such as thoroughly consolidated rock, the practical limit of a cutting goes far beyond that point at which a tunnel would be more economical. In such materials it is seldom necessary to take elaborate precautions with regard to the slopes of the cutting if the structure of the strata is favourable. Deep cuttings in yielding material become expensive, owing to the amount of excavation necessary to attain stable slopes. Cutting in gravel or sand cannot be safely carried to greater depths than 70 to 80 feet, while in clay this permissible depth is much less.

The procedure to be adopted in a given tunnel depends on the kind of material that will be encountered. The nature of this material is usually ascertained by borings or trial shafts which are sunk from the surface to the axial line of the tunnel. The important considerations are that the rock should stand cutting and be homogeneous in composition; that the work of tunnelling should not be rendered unduly expensive owing to hidden sections of loose or running ground; that care should be taken to prevent the influx of large volumes of water under great hydrostatic pressure, excessive rock temperatures or hot springs, discharge of noxious gases, etc.

If an exact idea of the structure and nature of the rocks of the area in which the tunnel is to be driven has been determined by a detailed geological examination, it is generally possible, unless the rocks have been subjected to exceedingly complex folding, to predict the conditions likely to be met with in driving the projected tunnel.

TUNNELS IN UNCONSOLIDATED ROCKS.—Under the designation Unconsolidated Rocks are included those soft or friable materials which either possess no cohesion or have a crushing strength of less than 4 tons per square foot. These materials consist of either

(A) Loose, separate grains, such as gravels, sand, clay, and the deeply decomposed representatives of the igneous, metamorphic, or compact, sedimentary rocks; or

(B) Of partially aggregated particles of the same types as the above, but forming marls, friable sandstones, and soft shales, etc.

All these varieties of unconsolidated rock may occur in a dry, moist, or wet condition, depending on whether the interstices between the grains or particles are devoid of, partly filled with, or completely filled with water or other liquid.

It is evident that the loose materials will in general possess little or no tenacity. In some kinds of clays, earthy materials, etc., there is considerable cohesion between the particles, particularly when the material is moist; and this imparts a tenacity which allows banks to stand for a time with a vertical or even an overhanging face (see "Applied Mechanics," by Rankine, 21st Edn., 1921, p. 212). This cohesion is gradually destroyed by exposure to air and moisture, so that in cuttings in such materials it is advisable to consider only the friction between the component particles and give the slope an inclination not greater than the angle of repose of the material.

The linings of shallow tunnels which have been driven through loose ground have the characteristics of two retaining walls facing each other with the space between arched over. The sides will be

subjected to the thrust of the horizontal material, while the arch will have to withstand the weight of the superincumbent material (see Fig. 36). It may be necessary to put an inverted arch on the floor of the tunnel to prevent wet material from being pushed up into the tunnel.

Tunnels driven at greater depths in loose material may, if the material is thoroughly waterlogged, be exposed to very severe pressures ; and the linings should in general be designed to withstand from 1.5 (for very fluid) to 2.5 (for viscous ground) times the normal hydrostatic pressure of water at the depth at which this running

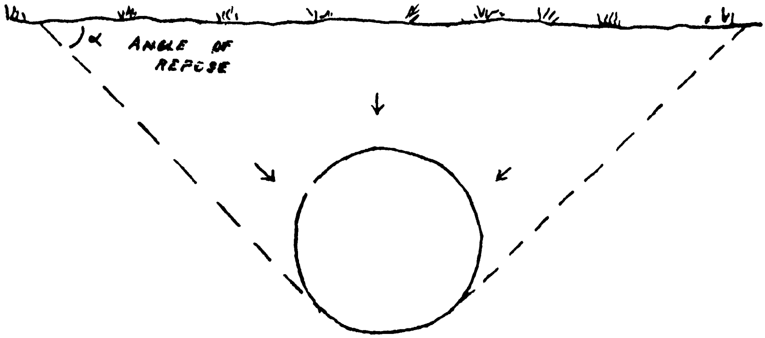


FIG 36.
Shallow tunnel in alluvium.

ground has been encountered (see table on page 172; also footnote below,* and text on page 239). If, on the other hand, the material is

* Extracts from "Applied Mechanics," Rankine, 21st. Ed., 1921, p. 264. If the depth of a tunnel beneath the surface of the ground is great compared with the height of its archway, the proper form for the line of pressures, which must lie within the middle third of the thickness of its arch, is the *elliptic linear* arch (see definition) in which the ratio of the horizontal to the vertical semi-axis is the square root of the ratio of the horizontal to the vertical pressure of the earth (see calculations inserted on page 53) ; that is to say

$$\frac{\text{Horizontal semi axis (half-span)}}{\text{vertical semi axis (rise)}} = c = \sqrt{\frac{p_y}{p_x}}$$

$$= \sqrt{\frac{1-\sin\varphi}{1+\sin\varphi}} \quad \text{where } \varphi = \angle \text{ of repose}$$

If the earth is firm and little liable to be disturbed, the proportion of the half-span, or horizontal semi-axis, to the rise, or vertical semi-axis, may be made *greater* than is given by the preceding equation, and the earth will still resist the additional horizontal thrust; but that proportion should never be made *less* than the value given by the equation, or the sides of the tunnel will be in danger of being forced inwards.

In a drainage tunnel the entire ellipse may be used as the figure of the arch; but in a railway tunnel, where it is necessary to have a flat floor, the sides and roof of the tunnel comprise in height the upper two-thirds or three-fourths of the ellipse, which is closed below by a circular segmental arch of slight curvature, its depression being one-eighth of the span, or thereabouts. The inverted arch serves to prevent the foundations of the sides of the tunnel from being forced inwards by the horizontal pressure of the tunnel.

The *exact* form for the line of pressures in the sides and roof of a tunnel is the *geostatic* arch (see definition below). This principle requires attention when the roof

moist but not porous, *e.g.* clay, it may possess sufficient tenacity to stand with an overhanging face above the tunnel (see Fig. 37). In this case the tunnel lining would not be subjected to the full weight of the superincumbent material. If the material remains moist and tenacious, the overlying weight may not exceed the amount W_2 shown in Fig. 37, but if the cohesion deteriorates, the weight may increase to W_1 (see same illustration) or more. Much, therefore, depends on the rapidity with which the lining is built in and the care with which falls of roof are prevented.

Tunnels driven in partially consolidated rocks, such as those in which the particles have squeezed together by pressure or whose component grains have been partly cemented with calcium carbonate, ferric hydroxide, silica, etc., will not be subject to severe falls of roof if the lining is built in as quickly as the driving goes forward and close up to the working face. Furthermore, since these rocks have an appreciable crushing strength, there is likely to be little or no actual rock weight on the tunnel lining though the pressure of contained water may be present.

TUNNELS IN CONSOLIDATED ROCK.—Tunnels driven through hard, massive, unfractured rocks do not require lining.

of the tunnel is near the surface. With the ordinates x_0 (= the depth from the surface to the crown of the tunnel) and x_1 (= the depth from the surface at its greatest horizontal diameter) as data, a *hydrostatic* arch (see definition below) is designed, and by contracting the horizontal co-ordinates in this design in the ratio $c = \sqrt{\frac{p_y}{p_x}}$, the result will be a geostatic arch.

CIRCULAR ARCHES for uniform fluid pressures. It is evident that linear arch, to resist a uniform normal pressure from without, should be circular; because, as the force to which it is subjected is similar all round, its figure ought to be similar to itself all round—a property possessed by the circular arch alone. (Rankine p. 183).

ELLIPTICAL ARCHES for uniform pressures. If a linear arch has to sustain the pressure of a mass in which the pair of conjugate thrusts at each point are uniform in amount and direction, but not equal to each other, all the forces acting parallel to any given direction will be altered from those which act in a fluid mass, by a given constant ratio; so that they may be represented by *parallel projections* of the lines which represent the forces which act in a fluid mass. Hence the figure of a linear arch which sustains such a system of pressures as that now considered, must be a parallel projection of a circle; that is an *ellipse*. (Rankine p. 184).

HYDROSTATIC ARCH which is a linear arch suited for sustaining normal pressures at each point, proportional, like that of a liquid in repose, to the depth below a given horizontal plane. (Rankine p. 190.)

GEOSTATIC ARCHES of a figure suited to sustain a pressure similar to that of earth, which consists, in a given plane, of a pair of conjugate pressures, one vertical and proportional to the depth below a given plane, horizontal or sloping, and the other parallel to the horizontal or sloping plane, and bearing to the vertical pressure a certain constant ratio depending on the nature of the material and other circumstances. (Rankine p. 196.)

STEREOSTATIC ARCH. A linear arch sustaining the pressure of a material in which, at any given point, there are a pair of conjugate pressures, one vertical and the other in a fixed direction, horizontal or inclined, but not bearing to each other any constant proportion, nor following any invariable law as to their intensities, except that of being of the same intensity throughout each plane which is conjugate to the vertical pressure. (Rankine, p. 198.)

There is generally no pressure acting on the sides, floor, or roof of a tunnel driven in granite and other large masses of igneous rock. Occasionally tunnels for part of their length may traverse massive beds of sandstone or limestone with the same advantages. In these cases the presence of joints in the rock, particularly if it is hard, makes the work of tunnelling much easier and cheaper.

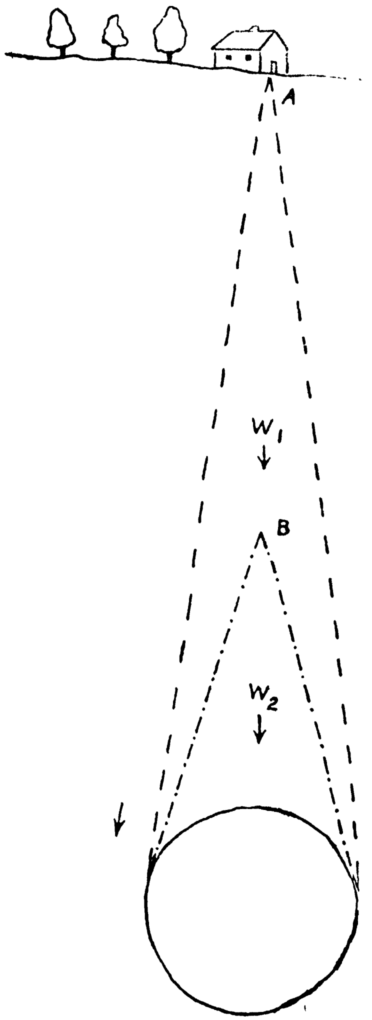


FIG. 37.
Tunnel in thick alluvium.

Long tunnels usually traverse various kinds of rock—these may consist of a complicated series of gneisses and schists, or beds of folded or tilted sedimentary strata. The alignment of the tunnel may be oblique to, or parallel with, the banding of the strata. A tunnel may cross the line of a fault, or pass through beds in the arch of a fractured anticlinal fold, or it may be cut through the strata in the trough of a synclinal fold. The beds themselves may vary from strong porous sandstones to soft impervious shales, and be gently or steeply inclined.

TUNNELS DRIVEN ALONG THE STRIKE.—Various examples of tunnels driven along the strike of bedded rocks are shown in the accompanying cross-sections (Figs. 38, 39 and 40). In Fig. 38 the tunnel is shown in a great mass of trap (dolerite). These rocks are fairly hard and tough and usually well jointed. The work of driving should not be very expensive unless large volumes of water are suddenly discharged from the larger joint fissures. Such a tunnel should not require lining. Fig. 39 represents a tunnel driven along the strike of a massive bed of sandstone. If the rock is open-textured, the tunnelling operations will be easy, though a steady inflow of water may have to be dealt with. The tunnel will not have to be lined. In Fig. 32C the tunnel is driven in horizontal strata. Most of the

tunnelling has been done in soft rock, shales and marls, and a strong sandstone is left to form the roof of the tunnel, while a hard limestone is exposed in the floor. This tunnel should not require lining if the sandstone is not heavily jointed. A certain amount of water will probably percolate into the tunnel, but this should not prove expensive to drain.

Fig. 41 shows a tunnel driven along the strike of tilted strata; part of the section is in soft shales and part is in strong sandstone. If the rocks are dry, there may be little or no trouble, but if there is an inflow of water along the junction of shales and sandstones in the roof of the tunnel, it may be better to avoid the sandstone by cutting the tunnel so as to touch the underlying limestone. In doing this the water troubles may be avoided, though in any case the tunnel will probably require lining to prevent falls of roof. There is, however, another danger. This is due to the possibility of relative movement between the hard and soft beds. In consolidated strata, consisting of hard and soft beds, there is, if the strata are tilted, a tendency for the hard beds to slide over the softer lower beds on their plane of contact. This would be likely to take place between the sandstone and the shale—particularly if the rocks were wet—consequently this danger would also be avoided by locating the tunnel to the right of the position shown in Fig. 41. In Fig. 42 the tunnel is driven along the strike of vertical strata. The same general remarks made with regard to Fig. 41 apply to this case. If the tunnel were cut entirely across the hard sandstone, an enormous weight might be suddenly brought to bear on the tunnel, owing to the sandstone being only supported by the friction of the beds on each side.

In the construction of the broad gauge Khyber railway on the North-West Frontier of India it has been necessary to drive over 30 tunnels. With regard to these, the Engineer-in-Chief, then Major, now Col. E. P. Anderson, D.S.O., R.E., mentioned the trouble he had had with one tunnel which ran along the strike, and in which the strata are nearly vertical. There was a narrow hard band almost over the centre of the tunnel and water had got down the joints. The result was a distinct extra weight on the crown of the arch (Fig. 43). F. H. Smith gives an interesting case of trouble with a tunnel on the Hill section of the Assam Railway. He says (*Mem. G.S.I.*, Vol. XXVIII, p. 73), when discussing the soft, steeply-inclined tertiary rocks, that;

"near Dumcherra a tunnel had been cut through a spur along the strike these shales. When the excavation was complete, the slab of vertical shales over the tunnel slipped bodily down into it, obliterating the tunnel, and leaving a corresponding cutting over the surface of the spur."

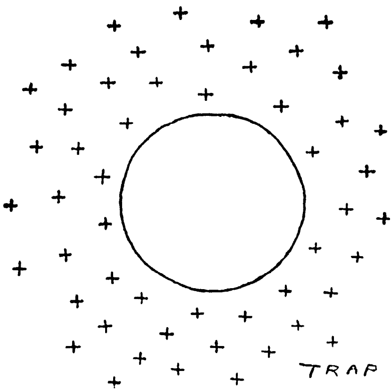


FIG. 38.
Tunnel in granite (uniform rock).

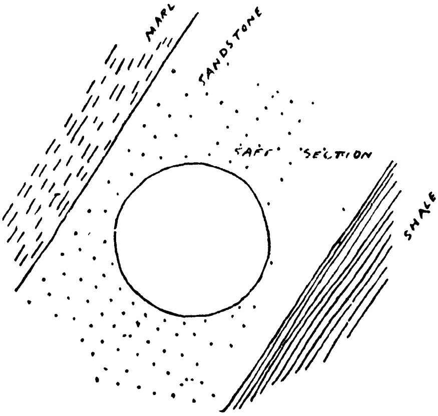


FIG. 39.
Tunnel in thick sandstone.

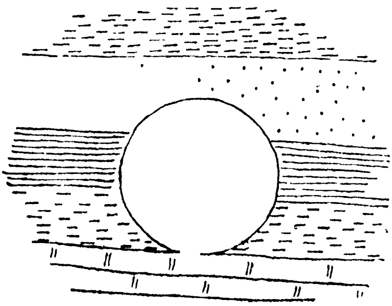


FIG. 40.
Tunnel in horizontal strata.

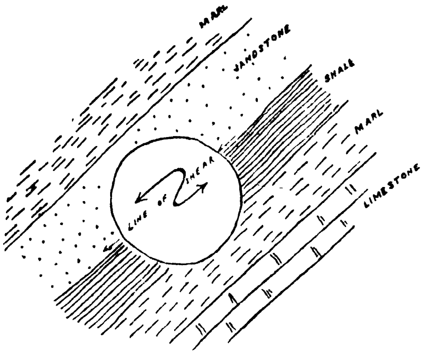


FIG. 41.
Tunnel in inclined beds.

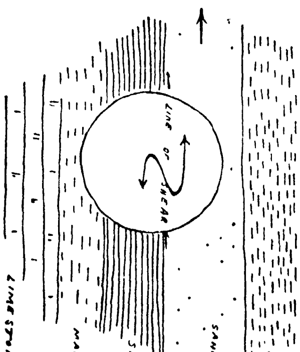


FIG. 42.
Tunnel in vertical beds.

In the tunnel sections just described, there are not likely to be sudden enormous inrushes of water. Hot springs and noxious gases, if present, would betray their presence long before they were actually met with. The strata throughout the length of the tunnel would have the same general characteristics.

TUNNELS DRIVEN ACROSS THE BEDDING.—When a tunnel has to traverse successive beds of different rocks, the work or tunnelling will not be uniform. Water troubles may be local and sudden, because water is nearly always encountered when a tunnel

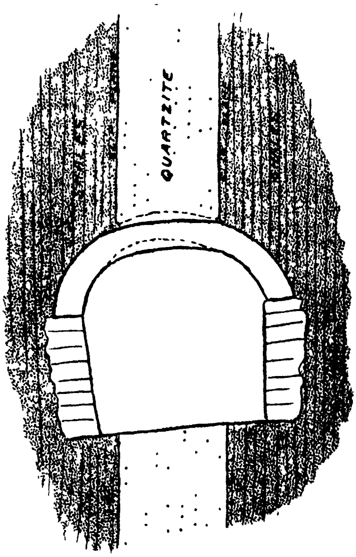


FIG. 43.
Faulty tunnel.

crosses tilted strata composed of alternate porous and impervious beds. The danger from relative movement of the beds will also be present if hard and soft beds alternate. If the rocks are not folded, and the succession of the beds and their inclination have been correctly ascertained, most of these troubles can be anticipated and efficiently dealt with. In folded strata the problem is far more complicated. The inclination of the beds must be carefully watched. There is usually cause for vigilance when the strata show a gentle inclination or dip, because this is an indication that an arch or trough fold is being approached. The greatest watchfulness is necessary when the alternate beds are different in character—*e.g.* sandstones with shales—and the folds are sharp (see Fig. 44). There is usually less danger from falls of roof in tunnels driven across the bedding of steeply-inclined strata than is the case if the beds are gently inclined. With unconsolidated rock, this danger is greater than with more compact rock.

Earthy sandstones, stiff marls and shales sometimes stand very well at the time of cutting, but frequently crumble on exposure; consequently, if tunnels in such rocks are not lined in a reasonable time, bad sections may develop.

Details regarding the Mont Cenis and the St. Gothard tunnels are always of interest to an engineer; for this reason the following details may prove of value. In *The Mont Cenis Tunnel* (see "Practical Tunnelling," by F. W. Sims, 4th Edn. by D. K. Clark, 1896, p. 246) the section from the south entrance was as follows:

1. Calcareous schist	5.8635 miles	(9,392.95 metres)
2. Limestone and dolomitic limestone	0.2210 "	(355.60 ")
3. Quartz(ite?)	0.2414 "	(388.50 ")
4. Carbonaceous schist	1.3027 "	(2,096.50 ")
Length in hard rock	7.6016 miles	

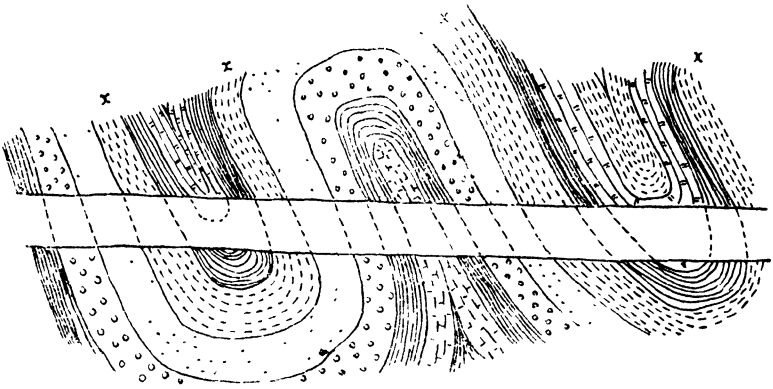


FIG. 44.
Tunnel in folded strata.

Wherever the rocks were homogeneous, although hard, the work of driving was easier. Soft and hard bands or veins gave considerable trouble, owing to the drills jamming.

Although there were only two points of attack—each entrance—no serious ventilation difficulties were experienced, the compressed air used for the machines producing sufficiently fresh air for the men.

Little damage appears to have resulted from the few falls of rock which occurred.

The temperature of a spring—under one mile of rock cover at a point 4.33 miles from the south end—was 84° F. The air temperature varied a good deal, but not above the figure given. Since the tunnel was completed, 25th December, 1870, the temperature in the middle varies from 80° F. to 90° F.

Except for a small section, the tunnel is lined throughout—masonry walls and brick arch.

The section met with in the *St. Gothard Tunnel* was as follows :

North end :

Granitic gneiss, more or less homogeneous	2200	metres
Gneiss, more or less schistose	450	,,
Crystalline limestone with grey marble ..	350	,,
Micaceous schist passing into gneiss.. ..	1300	,,
Gneiss, rich in mica, passing into mica schist	6600	,,
Mica schist hornblende..	1600	,,
Schistose gneiss	270	,,
Mica schist with quartz veins..	800	,,
Hornblende schist	1250	,,
Dolomite, gypsum, etc.	100	,,
Length in hard rock	14,920	metres

Dips at either end are steeply inward ; in the middle the foliation dips are vertical.

The mica schist with quartz, the hornblende schist, and the dolomite at the south end were crushed in places and discharged large quantities of water. Some of this water was under considerable pressure—3,000 gallons per minute—and great jets 1½ feet wide were suddenly projected into the tunnel. The flow from the tunnel at 2,300 metres was 4,600 gallons per minute. After this, little timbering was required and in the north section the rock was strong and hard. The temperature does not appear to have exceeded a maximum of 77° F. in the middle under a rock cover of 1,057 yards.

	Mont Cenis	St. Gothard	Simplon	Arlberg
	miles yards	miles yards	miles yards	miles yards
Length of tunnel ..	7 1734	9 549	12 460	6 640
Altitude N or E ..				
,, S or W ..				
,, highest pt. in tunnel ..	4,248 ft	3,788 ft.	2,314 ft.	4,300 ft.
Max. thickness of rock above tunnel	5,428 ft.	5,598 ft.	7,005 ft.	2,362 ft.
Max. temperature ..	85 F.	87 F.	104 F.	65 F.

HOT SPRINGS AND HIGH TEMPERATURES.—Hot springs can usually be detected in the neighbourhood of a tunnel. If none are on the surface, their occurrence in tunnels, except under high mountains, will be rare. If met with in the deeper drivages, it will usually be possible to dilute the hot water with the colder water of other springs in the same tunnel.

Records of temperatures taken in freshly exposed rocks in tunnels, in mountains or deep mines in various parts of the world indicate:

(1) That there is an increase of temperature towards the centre of the earth. This, from observations made in the St. Gothard tunnel, showed a rise of 1° F. for every 60 feet depth from the surface.

(2) However, the same temperature gradient is not true for all places. In regions of volcanic activity where hot springs occur, a gradient as high as 1° F. for every 30 feet depth has been recorded (see G. F. Becker, "The Geology of the Comstock Lode," *Monograph* III, *U.S. Geol. Surv., Washington*, 1882, p. 263); and in other regions, *e.g.* Calumet and Hecla Mine at Lake Superior, where the thermal conductivity of the rocks is low and the water percolation stationary or downward, the ratio may be only 1° F. for every 223 feet in depth (see Professor Agassiz, *Am. Jour. Sci.*, Vol. I, 1895, p. 503).

(3) Although the temperature gradient increases with the depth, tending towards a uniform ratio at great depths, the temperature gradient within 10,000 feet of the surface is not always regular—being affected by the conductivity of the stratified and massive rocks, their mode of occurrence and structure, and the absence or presence of ground water and the direction of water percolation.

(4) From all that has been said, it may be imagined that the rock temperature in various places is the same at equal depths. (See Professor J. D. Everett, "Evidence before the Royal Commission on Coal Supplies," London, 1904.)

"One of the largest thermal regions in the world is located on the north Island of New Zealand. In 1886 Mount Tarawera, which up to that time was looked upon as an extinct volcano, suddenly became violently active. The explosion blew out enough material to leave a rift in the mountain ¼ mile wide and 12 miles long. Many fumaroles were located in this rift. Intense solfataric activity continued for several years and thereupon resolved itself into a series of hot springs and a few steam jets."

In the Krisuvig region of Iceland it has been found that the infiltration of surface waters affects the behaviour of the hot springs.

"When the solfataras were artificially stopped up, the boiling springs and mud volcanoes rapidly increased in activity. When the surface waters were artificially dammed up, the boiling springs gave off steam instead of water."

Perhaps the area of greatest interest is that known as the "Valley of Ten Thousand Smokes," in the Katmai region of the Alaskan

Peninsula. A tremendous eruption appears to have occurred there in 1912. The valley contains numerous fumaroles. The temperatures of the gases escaping from the fumaroles ranged from 97 to 645 C., and the chief constituent of these gases was steam, which was present to the extent of about 99.9 per cent. (*Journal of Geology*, Vol. XXXII, 1924, p. 304.)

" Fenner has come to the conclusion that an acid magma was injected as a sill under the old valley floor and in part ejected as a rhyolitic pumice through the fractured floor, completely covering it to an unknown depth. (*Journal of Geology*, XXVIII, 1920, pp. 69-5, 606). Allan and Zies have come to the conclusion that the drainage of the mountains bordering the Valley is for the most part absorbed by the pumice, vaporized, and drawn into the more pervious walls of the fumarole vents by the jet action of the steam and gases escaping from the lava below. With such an agency at work it is evident that it will take but a few years to bring about an even greater decline in fumerole activity and an appreciable increase in hot spring activity."

Messrs. A. L. Day, E. T. Allen, L. H. Adams, and C. E. Orstrand have supplied very valuable data in a paper, " The Temperature of Hot Springs and the Sources of their Heat and Water supply," in the *Journal of Geology* (Vol. XXXII, No. 3, 1924). Although their investigations are chiefly in connection with the hot springs of the Lassen National Park, and the geysers of the Yellowstone National Park, yet their deductions are of importance. They have considered the possibility that radio-activity and chemical action play a part, but conclude that the heat is essentially of volcanic origin. They, however, consider that the water supply is not wholly from surface sources, *i.e.* all the water is not meteoric or vadose water, but some of it appears to be juvenile or magmatic water. Day and Allen say, speaking particularly of the " Devil's Kitchen " and " Bumpass Hell " springs :

" We have concluded that a hot magma must of necessity give off volcanic gases as well as heat, because all igneous rocks, which once were magmas themselves, give off similar gases when heated. Furthermore, heated igneous rocks almost invariably give off more steam than all other gases put together."

In the case of the Yellowstone Park area, however, Orstrand says :

" The behaviour of the springs and geysers in the Park has been satisfactorily explained by Dr. T. A. Jaggar on the basis of convection currents and artesian flow of water which has its source in the adjacent mountains."

The rock temperatures encountered in various long tunnels driven deep under mountains have so far not been found to affect seriously the working operations, when compressed air drills and heading machines have been used. Coarse-textured, igneous rocks seldom influence the air temperatures to an uncomfortable degree. Rather

severe temperatures were met with in the Simplon tunnel and traced by Professor J. Joly as due to appreciable amounts of radio-active material.

POWER FROM THE EARTH'S HEAT.*—In a discussion opened by Sir Charles Parsons, suggestions were made with a view to utilising the interior heat of the earth for power purposes. It was pointed out that 10,000 h.p. was being developed at La Darello in Italy, and other projects were being considered for obtaining power from the volcanic heat of Vesuvius. In the course of the discussion it was stated that although the average geothermic gradient was supposed to be 1° F. for every 72 feet descent, this was not found to be correct in various places, *e.g.* the Morro Velho Mine in Brazil (216 feet per 1° F.) and the Village Deep in the Rand (250 feet per 1° F.). H. F. Marriot thought that the practical limit of boring had been reached in the West Virginian bore hole, 7,579 feet. In conclusion, it was thought that this mode of obtaining power was at present outside the limit of our engineering ability. (See J. S. Haldane's paper, "The Spontaneous Firing of Coal," *The Colliery Guardian*, Vol. CXIII, 1917, p. 1165.)

SPONTANEOUS HEATING.—It is now generally agreed that the heating produced in certain coal seams, carbonaceous shales, and pyritiferous strata is due to one or more of the following three agencies:

(1) Oxidation of the organic constituents;
(2) Decomposition of iron pyrite (marcasite); and
(3) The crush and grinding produced by pressure.

Some coal seams are particularly liable to fire as a result of spontaneous heating, which becomes noticeable by the peculiar smell "fire stink," and the emission of large quantities of carbonic acid gas. This combustion may be accelerated by the presence of iron pyrite in the coal and the formation of ferrous and ferric sulphate as a result of its oxidation. It is known that the oxidation of marcasite alone is incapable of starting a fire. The friction caused by slippings due to the pressure on a coal pillar, and the formation of cracks, and the grinding of the sides of these fissure faces against each other, may produce heat and small coal. This crushed, warm coal would oxidise more quickly, with the result that the heating would be rapid and there would be a sudden outbreak of fire. (See "Text Book of Coal Mining," by H. W. Hughes, 5th Edn., 1904, pp. 220-221.)

* The hot springs of the Province of Pisa (Italy) which have long been used as a source of boric acid have recently been employed for the generation of power. The natural steam is made to circulate around aluminium tubes which form part of a water-tube boiler. In this way steam is developed in the boiler and utilized for power purposes in the usual way. Three units each of 2,500 kilowatts were erected in 1916. Two of these units are in operation. (See "Engineering," May 10 and 24, 1918, paper by Ugo Funaioli, "The Larderello Natural Steam Power Plant.")

The best remedy for the prevention of dangerous heating is cooling, either with a current of cold air or water, and the removal of all fine or crushed material.

(1) "Spontaneous Combustion of Coal" (see *Colliery Guardian*, Vol. CVII, 1914, p. 242 and pp. 43, 97, 153, 260, 315, 368, 423, 475, 533, 585 and 642.) The evidence produced showed that the greatest danger was to be expected in gassy mines.

(2) There is an interesting paper by Professor Henry Briggs (see *Colliery Guardian*, Vol. CXXIV, 1922, pp. 1225 and 1272) in which attention is drawn to the heat generated by crush pressures which produce a grinding effect and comminute the rock.

(3) E. J. Moynihan, in his paper "Rock Temperatures" (see *Colliery Guardian*, Vol. CVIII, 1915, p. 534) says that as a rule the mere fact of tunnelling into rock, and thus allowing an access of air, is usually followed by a fall in temperature. This is particularly true when the work of tunnelling is effected by compressed air drills, etc. He calculates that the heating effect of candles and the breathing of the workers would not raise the air temperature in a tunnel very much. He follows up these remarks by saying that only in the case of coal, which rapidly oxidises, will there be a dangerous increase of temperature.

(4) In his paper, "The Atmospheric Oxidation of Iron Pyrite" (see *Colliery Guardian*, Vol. CXI, 1916, p. 1102), T. F. Winmill discusses the decomposition of the marcasite and pyrite in coal. He states that it is only when these metallic sulphides are present in large quantities, 20 to 30 per cent., and the coal is in a powdered condition, that rapid oxidation and possible ignition may take place. He thinks that pyrite and marcasite decompose equally rapidly when finely powdered, although marcasite is more liable to oxidation in a normal crystalline condition. He does not produce enough data for these observations.

(5) "Black Damp in Mines," *Colliery Guardian*, Vol. CXIII, 1917, p. 71, from *U.S. Bureau of Mines, Bull.* 105. Carbon dioxide and nitrogen from mines: 3 to 4 per cent. affects breathing; when oxygen percentage below 13 per cent.—bad; when oxygen percentage below 7 per cent.—very bad, immediate effect.

One of the most extraordinary suggestions put forward to account for the increased temperature in the workings of a mine is that advanced

by T. A. Rickard in his "Journeys of Observation," 1907, p. 105. He says:

"the air underground is very warm. On the second level of the Mexico mine it was 85°; in the shaft (owing to steam pipes) fully 100°F. In the cross-cut from the 286-foot level going west from the Somera shaft the temperature was 95°, and in the cross-cut at 1,086-feet it was up to 105°, by reason of poor ventilation and escaping steam. The general temperature in the workings is 60° to 70°. The heat is due largely to the action of water on the lime in the shale—slaking it—and it may be due also to the crushing of the shale, which is often seen to press heavily on the timbers."

The occurrence of free, calcined lime, appears quite unnatural, and the explanation given above is probably incorrect.

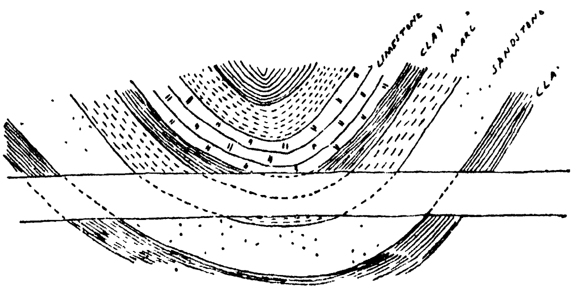


FIG. 45
Tunnel through synclinal.

NOXIOUS GASES.—Certain limestones, carbonaceous beds, and pyritiferous, argillaceous rocks are the usual varieties of strata from which noxious gases are evolved. Accumulations of gas may be present, or the gases may be given off gradually when particular beds are exposed. However, these dangers can usually be suspected during the preliminary geological examination by the detection of iron pyrites, oil or alkaline substances in the associated rocks. The harmful effects of such gases can generally be greatly minimised by establishing an efficient system of ventilation and by carefully sealing these particular beds when they are encountered.

TUNNELS IN TROUGH FOLDS.—Tunnels which are driven across the axis of a trough fold of the strata may encounter serious water difficulties and be subject to falls of roof (see Fig. 45). Splendid artesian conditions may exist, so that when a tunnel taps a porous bed enormous volumes of water under great pressure may be discharged into the tunnel. If hard rocks occur, it is probable that water will occur in the numerous joint-planes. Also, owing to the jointing being radial to the curve of the folds, the resulting blocks will have the shape of inverted keystones. These may suddenly fall into the tunnel with fatal consequences.

A tunnel driven in and parallel to the axis of a syncline will naturally be subject to these rock-falls to a greater degree, because such dangers are present throughout the length of the section in the syncline.

TUNNELS IN ARCHED FOLDS.—There is, as a rule, less likelihood of serious water trouble in sections where a tunnel cuts across the axis of an anticline in bedded rocks than in inclined strata. There is also less danger from sudden rock falls, because the blocks will be in the shape of keystones and consequently are unlikely to fall into the tunnel. If, however, the rocks are severely crushed, as they sometimes are on the lower side of the arched fold, the shattered material may cause small falls of roof. Similar remarks apply to that length of a tunnel which is driven parallel to the axis of an anticline (see Fig. 46).

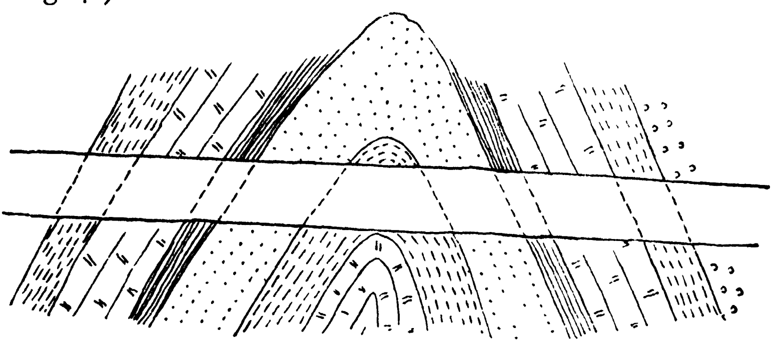


FIG. 46.
Tunnel through anticlinal.

TUNNELS DRIVEN ACROSS FAULTS.—A tunnel should never be driven along a fault which has not been mineralised. The plane of a fault is usually a zone for the release of earth strain. Displacements of the rock on each side of the fault frequently take place, and this movement may lead to the destruction of the tunnel.

Large volumes of water under great pressure are frequently present at points where a tunnel crosses the plane of a fault—particularly if porous beds on one side dip towards impervious beds on the other side of the fault plane. Relative displacement of the strata on opposite sides of a fault-plane is an obvious source of danger, more especially if the rocks on both sides of the fault are well consolidated beds of hard material. In less consolidated strata, this danger may often be more imaginary than real. Cases are known, *e.g.* the mile-long Barog tunnel on the Kalka-Simla railway, where a tunnel, which traverses beds of hard rock, crosses a fault and enters softer rocks, has not been damaged by a severe local earthquake. The shock of the earthquake appears to have been absorbed by the compressibility of the softer rocks of the tunnel under consideration. If thrust faulting is present and

the beds involved are soft or soluble, *e.g.* limestones or salt marls, dangerous falls of roof are almost certain to follow excavation in these places, and serious water troubles are seldom absent from such conditions. In any case, an exceedingly strong lining will be required in these sections. If the plane of the thrust fault is inclined at a low angle, the tunnelling through the section of dangerous ground may prove too costly to be carried out.

WATER IN TUNNELS.—The amount of water and the rate of its discharge into the tunnel depends on numerous factors. Among the more important of these are the contour of the hill through which a tunnel is to be driven, the extent of the out-crop of a porous bed and the slope of the ground on which this bed out-crops, the jointed nature of the rocks, the presence of faults, and, of course, the local rainfall —chiefly its rate of precipitation. Less water may be encountered in open-textured rocks which out-crop on precipitous hill-sides than may be expected; whereas fissured rocks which are exposed on level ground may contain large volumes of water.

As one example of the trouble experienced in making a tunnel under a river, the following, taken from "Ways and Works in India," by G. W. Macgeorge, 1904, p. 87, is interesting:

"The great difficulties to be encountered in dealing with such a torrent as the Indus at Attock, subject to so great an ordinary flood rise, and liable, moreover, to extraordinary floods of uncertain limits, led at length to a well-considered proposal in the year 1859, to turn the more important of these difficulties by the substitution of an under passage or tunnel beneath the river. Careful studies entered into showed that the banks and bed of the Indus at Attock were composed of slate rock, moderately easy to work, and apparently free from fissures likely to seriously endanger or enhance the cost of the work. A scheme was therefore elaborated in full detail for a brick-lined tunnel 1215 feet long, 24 feet wide, and 20 feet high, to extend underneath the river, with a roadway 82 feet below low water level. It was proposed that the level of this under passage should be reached by descending tunnel approaches on either side of the river, each on a grade of 1 in 20; the entrances being placed at 100 feet above the level of winter flow—that is, at 182 feet above the floor of the actual river tunnel. The total length of the complete gallery, including the approach grades, would have been 7,215 feet, or over $1\frac{1}{3}$ miles. The tunnel was to be ventilated by air shafts placed 600 feet apart (except at the river section, where the interval would be longer) in the shape of hollow cut-water towers, having their summits placed above the reach of floods, and the gallery was to be lighted throughout with oil-gas manufactured on the spot. Duplicate pumping engines were to be provided for keeping the tunnel clear of water, and provision was also made for its rapid flooding by means of a syphon at any time under military necessity. The estimated cost of this project was £104,408. . . . and in March 1860, the sinking of the necessary

shafts on either bank of the river was commenced by military labour. The leakage of water, however, was found to be heavier than anticipated . . . . The drift underneath the river—about 6 feet by 3 feet in section—and the vertical shafts on either bank were . . . completed, but the execution of the complete tunnel project was at the time postponed.

" The work actually carried out was as follows. On the east bank of the river a shaft, 168 feet deep, with 8 feet extra for drainage, was sunk through the hard rock. On the west side a similar shaft—situated 1505 feet from the first—was sunk 93 feet deep, with 8 feet extra for drainage. The position of the west shaft being near the river edge, and much below summer water level, a hollow pier of masonry was built up to keep out the floods. From near the bottom of the shafts two galleries pierced northward for a distance of 25 feet, each 6 feet high and 3 feet wide, to meet the main drift of the same dimensions, which was carried under the river, and on the east side of the river at the level of the grand trunk road, a gallery was driven to meet the vertical shaft. Owing to fissures in the rock, and the influx of water, both shafts were lined with brick masonry. The drift-gallery beneath the torrent of the Indus was made with a slope of inclination of 1 in 300 towards the east, or Attock side, in order to drain off the water. The work throughout was performed by a small detachment of the 24th Punjab Infantry, aided and directed by six European miners ; the object of the drift heading being to test the nature of the rock, and the feasibility and probable cost of carrying out a complete tunnel scheme.

" After some discussion it was decided on various grounds to abandon the tunnel project, it being held that an overhead bridge would be a more suitable crossing, and less costly to maintain. The miners, were, therefore, withdrawn, and the heading allowed to fill with water. In the year 1870—when Lord Mayo, the Governor-General, came to Attock—the drift-gallery was pumped out for his inspection, and it was found quite uninjured. The proposal to complete the work was reconsidered, but it was again rejected in favour of the combined road and railway bridge, which now crosses the Indus at Attock, a remarkably fine work. . . . ."

PRESSURE TUNNELS.—In many cases tunnels are lined in order that the tunnel may be kept free from falls of loose rock or from an influx of large volumes of water. The lining of the tunnel is, therefore, subject either to the weight of the loose earth, or to the pressure of the surrounding water, or both. Occasionally a tunnel acts as a duct for a canal ; and, more rarely, a tunnel may function as part of a pipe-line for water under considerable pressure. In such circumstances, it is obvious that there will be an outward pressure on the lining of the tunnel.

The Sutlej River Hydro-electric Scheme includes a projected tunnel, a mile long, which is designed to conduct water under a 160-foot head, when the great 395-foot high Bhakra dam is built. This

pressure of water, which is approximately 70 lbs. per square inch, is as great as the pressure in many boilers. Water, under this pressure, would burst most masonry linings if the strata behind the lining were not incompressible. In hard rocks, if the joints are carefully grouted up, there would probably be no necessity to line the tunnel. Limestones, however hard, are always soluble, and it would be unwise to leave those sections of a tunnel unlined in which soluble rocks were exposed. There would not only be leakage of water from the tunnel, but in time this escape and its solvent action might result in a collapse of a portion of the tunnel.

Most rocks, including soft sandstones, can be treated as incompressible if exposed to pressure not exceeding 4,000 lbs. per square inch. Sand and gravel, if unable to escape laterally, will also for practical purposes be incompressible under these pressures. Tunnels through these rocks would in any case be lined; so that if a little care were exercised to ensure the loose material behind the lining being rammed into place, there need be no fear of the tunnel being burst by the "give" of the lining. Clays, on the other hand, are compressible even when subject to moderate pressures; consequently, tunnel sections in clayey strata require special treatment, *e.g.* by putting in steel tubing or casing, etc.

EFFECT OF EARTHQUAKES.—In seismic regions there is naturally some danger to be apprehended should a tunnel be subject to an earthquake shock. In unlined tunnels in hard rocks the dangers are seldom made real, but if the tunnel has been lined with large stone block arches, a considerable amount of damage may occur at the entrances. At these points the seismic waves are felt most strongly as a rule. Brick arches at these places are generally more reliable than stonework of large blocks. The following extract from "Ways and Works in India," G. W. Macgeorge, 1904, p. 399, may prove elucidating:

"The Khojak tunnel—the largest railway or other tunnel in India—has a total length of 12,870 feet, or just under 2½ miles and runs . . . through the Khwaja Amran range . . . the works throughout this difficult section of line occupied nearly four years in all."

"To convey an idea of the vicissitudes and dangers to which some Indian railways are exposed, the following press notice of the extraordinary effects of an earthquake which occurred on 20th December, 1892, in the Quetta district and southern parts of Afghanistan, will be of interest:—

"In the neighbourhood of the Khwaja Amran range the shock was very severe; a tower in one of the block-houses was cracked, some walls were shattered, chimneys were shaken down, and several old houses tumbled into ruins. In the Khojak tunnel the noise was deafening, and workmen engaged on the roofing were thrown from

their perches to the ground. There was, however, nothing very extraordinary in these effects; it was on the line of railway between the tunnel and Old Chaman that a curious phenomenon occurred. At mile 643 (from Karachi) four or five lengths of rail were found to have been bent by being opened out sideways, while all the joints nearby were jammed up tightly. The bent rails were removed, and the work of putting in new ones was proceeded with. What was the surprise of the engineers to discover that the measure was less by 2 feet 6 inches than the original length. This was due to a crack or 'sheer' which crossed the railway bank at an angle of about 18 degrees, exactly at the place where the track had been contracted. This crack bears a little east of the meridian, passes through the old bazaar near Chaman Fort, and, according to native reports, extends across the main range of the Khwaja Amran eighteen miles away. The fact clearly established by the shortening of the railway track (says the 'Pioneer') is that the earth's crust has contracted 2½ feet in the vicinity of the Khojak. . . . The evidence is indisputable, and photographs taken on the spot show exactly how the rails were twisted out of the straight. One rather shrinks from thinking what the effect on the Khojak tunnel would have been had it come within the destructive action of the shock."

SHAFTS.—The location of a shaft for mining or engineering purposes is usually fixed after making a geological examination of the area of the proposed site. Frequently the actual spot is chosen after boring. The cores of the boring provide information of the kind of rocks which will be encountered.

Glen George and J. H. Evans (see *Colliery Guardian*, Vol. CX, 1916, p. 418) describe the difficulties encountered and overcome in sinking a shaft through an unexpected fault at Dhobidih Colliery in the Bengal coalfields. Before striking the fault, they had to deal with large volumes of water; when this was dealt with the shaft suddenly collapsed after further sinking. On examining the side which had slipped in, it was found that the shaft had encountered a reverse fault.

In the case of long tunnels these shafts serve a treble purpose. They supply data for each section of the tunnel, allow of greater speed in tunnelling, and do away with elaborate ventilation. For example, in the important Lochaber water-power scheme in Scotland, the longest tunnel is about 16 miles long. At least 14 shafts have been sunk from the surface to the line of the tunnel to give twice that number of points from which to work in addition to the two ends. This procedure is sometimes modified in driving tunnels under rivers. In making the tunnel under the Thames, between Stepney and Rotherhithe, an entry was effected to the line of the tunnel by means of caissons fixed in the river itself. The cross-channel tunnel will, however, necessitate special operations, as both shafts and caissons are impracticable. In this case it is known that some of the strata are

continuous, although not in an absolutely straight line from shore to shore. The proposed scheme, therefore, aims at working from either end in a particular bed. If an impervious stratum is chosen, and the bed is sufficiently thick, the only drawback to the scheme is the time which will be taken in tunnelling from two working points and the arrangement of efficient ventilation.

CHAPTER XI

RETAINING AND PROTECTING WALLS

WALLS which are built to impound water are known as dams; whereas those which are constructed to retain loose materials, rock debris, etc. are usually called revetments.

DAMS.—In designing a dam the engineer always determines the amount and direction of the thrust on the foundations of the dam. This force is the resultant of the push of the water and the weight of the dam itself. The materials utilised and the method of construction of a dam should be such that the dam will safely keep these forces in equilibrium. Much, however, depends on the choice of the site for the foundations of the dam. The underlying rock must be strong enough to take the weight of the dam and withstand the resultant thrust. In addition, these rocks must be sufficiently impervious in texture and free from open fissures to prevent serious leakage of the impounded water. If this water gets under the dam with sufficient hydrostatic pressure, the upward component of this force will partly counteract the weight of the dam and thereby add to the danger of the dam being rolled over by the horizontal push of the impounded water.

The most suitable site for a dam is on a strong massive band of impervious rock. Granite free from joints and fissures would make an excellent foundation for any dam. Such locations are not common in actual practice. In most instances, valleys are carved out along the lamination of the strata; consequently, the strike of the beds may be at right angles to the length of the dam. When a river breaks across a ridge by cutting a deep gorge at right angles to the strike of bedded or foliated rocks, an ideal dam site may be found in the gorge. Generally, however, dams have to be built in shallow valleys on rocks which are seldom absolutely satisfactory. Much is left to the skill of the engineer to make the foundations good.

DAMS ON UNCONSOLIDATED ROCKS.—Dams intended to hold up a great depth of water cannot be efficiently founded on soft or porous unconsolidated strata, such as sand or loam or clay. In the former case the loss by percolation would be considerable and the dam

might be destroyed by overturning; high dams built on clay would be pushed along their foundations and bulge and most probably collapse. It is to the credit of the engineer that records of such failures are exceedingly few. Although it is dangerous to build high dams (above 75 feet) on loose material, and unwise to risk dams of moderate height (30 to 75 feet) on such foundations, it is possible to construct efficient low-pressure dams on such ground, provided there are no open cracks or fissures in these foundations. If the underlying material is clay, there should be no difficulty in testing for interbedded porous beds, and, if these are not present, the building of a thoroughly reliable water-tight dam should be practicable. In the event of the underlying material being a bed of sand, the conditions are entirely different.

Professor Boyd Dawkins (see James Forrest's Lecture "On the Relation of Geology to Engineering," *Min. Proc. Civil Engineers*, Vol. CXXXIV, 1898, p. 254) called attention to discoveries made by that great engineer, Robert Stephenson, in connection with the flow of water through sands. In driving the Kilsby tunnel, near Rugby, beds of waterlogged sands were encountered, and it was first thought that the whole of these sands would have to be de-watered by pumping before satisfactory progress could be made. Stephenson, however, soon discovered that owing to the resistance which the water encountered in its passage through the sands to the pumps, the water-surface occupied an inclined position. By pumping on the precise level of the tunnel alignment, a dry valley in the water-surface of the sands was made and the work of construction continued without de-watering the whole of the sand.

W. R. Baldwin-Wiseman has experimentally determined the influence of pressure and porosity on the motion of sub-surface water (see *Quart. Jour. Geol. Soc.*, Vol. LXIII, 1907, p. 80, etc.). He found that the rate of flow of water (D) through filter-beds varied with the thickness of the sand (L), the pressure of the water (H), and the size of the sand grains (G).

(1) When H/L=5, and sand under 60 mesh.

H in feet	L in feet	D cubic feet per hour per square foot of sand
1.25	0.25	11.6
21.25	4.25	2.7

(2) When H/L=2.

G=under 60 mesh	on 50	on 40	on 30	on 20	on 10	on 6
D was .. 1.8	4.2	7.0	12.3	21.7	35.4	43.2
(3) When H/L=1.						
D was .. 1.4	3.2	4.9	9.2	15.1	30.4	37.2

A low dam of great width, if built of impervious materials and water-tight in itself, would, by its weight, compress the sand under its foundations and decrease the size of the interstitial spaces between the grains, the leakage from the reservoir would therefore be reduced owing to the increased interstitial friction of the sand. With small depths of water in the reservoir, and careful building of the dam, the loss by leakage would be far less than might be anticipated.

The building of dams under these conditions is, however, seldom warranted. If the thickness of the sand is less than 12 to 15 feet, it may prove cheaper to build a normal dam with its foundations on the underlying rock than to construct an abnormally wide dam. On the other hand, if the thickness of the sand is considerable (above 30 to 40 feet), no dam may be necessary, as abundant supplies of water will probably be obtainable by pumping from filter cribs in the sand.

The influence of the size of the grains of sand and gravel on the rate of infiltration has been given by J. M. Lacey ("Hydrology and Ground Water") for a hole 6 inches in diameter as follows:

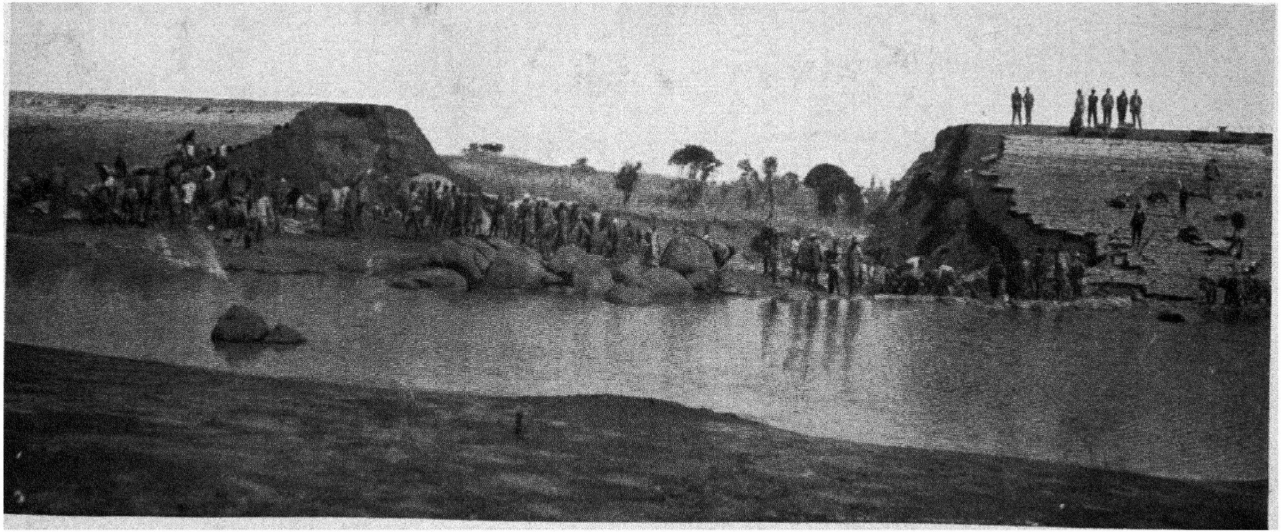
In fine sand rate of filtration	..	4,000 gallons a day.
In medium sand rate of filtration	..	30,000 " "
In coarse sand rate of filtration	..	80,000 " "
In gravel free of sand rate of filtration		500,000 " "

Earth dams (see paper on "Reservoirs with High Earth Dams in Western India," by W. L. Strange, *Min. Proc. Inst. C.E.*, Vol. CXXXII, 1898, p. 158) although widely used rarely get careful attention.

The limit of height for pure earth dams is normally considered to be 60 feet. However, with masonry core walls and suitable earth material, dams of 75 to 100 feet or more in height can be safely constructed. Perhaps the highest earth dam in the world was the one at Estrecho de Ricutes, near Lorca, Murcia, Spain, which was completed to a height of 150 feet in 1789, first fully impounded water in February, 1802, but was breached in April of the same year; the reservoir discharged itself, destroying part of Lorca and drowning 600 people. (See *The Engineer*, Vol. LXIII, p. 208.) The cause of failure was not known.

From the geological point of view the two points of importance are (1) that there is not too great depth of soft clay under the foundations of a high earth dam, because the weight of the dam may cause a subsidence of the dam by compressing the clay below; and (2) the nature of the material used in the construction of the dam. In Western India the material known as "black-cotton soil" has frequently been used in dams of this type—*e.g.* the Waghad dam in the Nasik district, which was to have had a maximum height of 95 feet, but was only built to 87 feet, was seriously damaged by the slips which occurred

PHOTOGRAPH XVI.



BREACHED DAM. [*Photo by H. S. Gordon, Esq.*

The reservoir overflowed and the consequent erosion of the embankment led to the destruction of the dam. A flood discharge is best deflected through an adequate spillway.

THE SALISBURY DAM, RHODESIA (1923).

[*To face page* 226.

on its down-stream face, due to the treacherous character of the " black-cotton soil " which had been used in its construction.

This material is subject to a very great increase in volume when it gets wet, as it absorbs moisture readily. Once wet, " black-cotton soil," however well rammed, loses all cohesion and behaves like a viscous fluid; and for this reason should never be used in the earth-work of a dam. The material appears to be peculiar to the Deccan region of the Indian peninsula, and is specially mentioned in this connection as a warning against the use of certain clays and marls of other countries which may have similar physical properties.

As an example of prudence in the choice of suitable material may be quoted the following: The most notable work was the Anasagur dam, west of Jaipur city (Rajputana, India), which crossed the very deep nullah flowing from the Jaipur hills to the north. It was about 1,500 feet long by 60 to 70 feet high, with a water slope of 4 to 1, and consisted entirely of light sandy soil, with a 20-foot roadway on top, and was situated up-stream of the great masonry dam (now in ruins) built by the Raja of Jaipur about 1865, and which failed when full, owing partly to the water escaping behind the vertical sandy cliffs on which the ends abutted. Colonel Jacob, profiting by this failure, built his dam of the same material as the soil at the site; the ends of the dam were well bonded into the cliffs on each side, and thus any creep of the water around the wings has been stopped. No core wall or puddle was used in this work (see C. H. Crondace; *Min. Proc. Inst.C.E.*, Vol. CXXXII, p. 243). It is necessary to mention here that there is a certain leakage allowed for from the irrigation reservoir beds under dams in many parts of Rajputana, because this percolation is beneficial to the down-stream well irrigation (often for many miles), as it raises the spring level of the wells for a long distance down the drainage line on each side.

The weight of structures on foundations of various kinds of rock are, normally, limited to the following amounts for safe work:

1. Soft clay and loam carry 1 ton per square foot.
2. Ordinary clay or dry sand mixed with clay carries 2 tons per square foot.
3. Dry sand and hard dry clay carry 3 tons per square foot.
4. Rammed dry clay and firm coarse sand carry 4 tons per square foot.
5. Firm coarse sand or gravel carries 5 tons per square foot.
6. Hard shale carries 8 tons per square foot.
7. Common brickwork carries 12 tons per square foot.
8. Sandstone masonry carries 20 tons per square foot.
9. Hard limestone masonry carries 25 tons per square foot.
10. Granite masonry carries 30 tons per square foot.

Thus it is seen that although the soft clay will support a column of 36 feet of water (pressure of which is, roughly, 1 ton per square foot), it will not support the weight of a dam 36 feet high, unless enormously wide foundations are made to carry a relatively slender-sectioned dam. According to these figures, there should be no difficulty in supporting 36 feet of water by a dam on sand foundations, provided the thrust on the foundations is safely held.

DAMS ON SOLID ROCK.—Massive rocks, such as granites, dolerites or other ingenous types, and gneisses and schists, quartzites, hard limestones, and even fine-textured sandstones, if free from open joints and fissures, make excellent foundations for dams. In porous rocks, such as open-textured sandstones, decomposed granite or dolerite, etc., and the peculiar substance known as laterite, there will be considerable percolation if there is a great depth of water at the dam.

Interstitial percolation does not necessarily lead to serious leakage losses if obviously porous rock is avoided. By far the most serious defects in the massive rocks are the open cracks and joints which are so repeatedly met with in cutting foundations in these rocks. Such fissures discharge enormous volumes of water when the sluice gates are closed and water impounded. In limestones, the solvent action of the water steadily enlarges the channels of escape, until these may become so large that they collapse, and the subsidence which takes place may destroy the dam. In the majority of cases, these fissures are of small dimensions and do not extend far into the rock; consequently, it is possible to trace their ramifications and seal them up with cement grouting. The joint planes of massive rocks, *e.g.*, granite, on the other hand, usually have deeper connections, which may prove difficult to render water-tight. The most troublesome kind of fissure is that due to faulting—particularly if it crosses the length of a dam obliquely—because it may be impossible, at reasonable cost, to seal it against leakage of water from a reservoir. Further, the strata on opposite sides of a fault-plane are always liable to displacement during earthquakes, and such movement would, besides re-opening the fault-fissure, involve the rupture of the dam. It is hardly necessary to add that no important dam should be built across a fault-plane, even in regions free from earthquakes. Dams should be built on the up-stream side of a fault which crosses a valley parallel to the length of a proposed dam.

FLOOD DAMS.—In the case of flood dams there is less need for care because the impounded water is rapidly discharged. The danger that may be anticipated in such cases arises from the fact that the discharging flow, although regulated, necessitates attention to the

stream bed just below the dam. On soft beds there is a possibility of deep scouring which might undermine the dam. Many flood-dams hold up a permanent volume of water and this, by percolating into faulted limestone for example, may lead to the collapse of the dam, or, by infiltrating into the workings of important mines, result in flooding them. A very important site for a big dam on the Damodar river, in the chief coalfield area of India, had to be abandoned because it was discovered that the impounded water would cover the out-crop of a strong fault for a length of 4 miles; this fault constitutes the

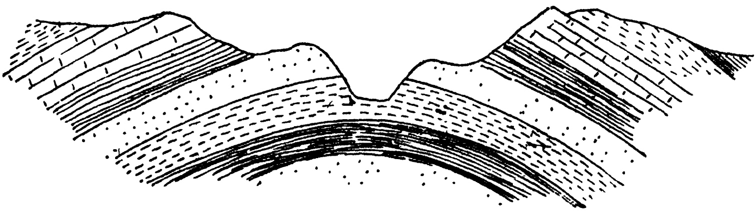


FIG. 47.
Erosian valley (low anticlinal)

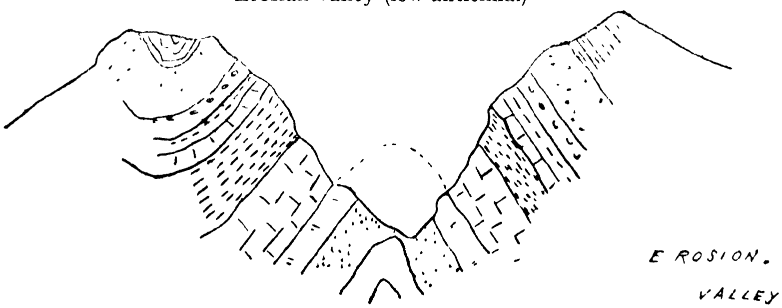


FIG. 48.
Erosion valley (sharp anticlinal).

south boundary of the Jheria coalfield. It was rightly thought that considerable leakage would take place from the river into the workings of the adjacent collieries, these mines were already subject to serious water trouble and any additional water might have resulted in the closing of the workings. The recent (1934) earthquake in Bihar affected the faults in this coalfield and confirmed the opinions (given above) of nearly 15 years ago.

DAMS ON BEDDED ROCKS.—A large number of dams are built on bedded or laminated or foliated rocks. The planes of bedding or foliation may be parallel to or across the length of the dam. They may be inclined at an angle or they may be buckled into close folds. The individual beds of the strata may consist of porous rock intercalated with impervious layers. Each site requires careful examination. Figs. 47 and 48, show cross-sections of typical erosion valleys in mountainocous untry. In each case the valley follows the

axis of an anticlinal fold. In Fig. 47 the bed and banks of the stream in the valley consist of marls which are overlaid by porous sandstones. A dam built in this valley will be water-tight up to the height of the marls; above that level leakage will take place, through the sandstone, round the abutments of the dam. In Fig. 48, a bed of sandstone is exposed in the bed of the stream; it is bent in an arched fold and is almost certain to be heavily fractured. The work of building the dam will prove costly, as it will be necessary to make the foundations of such a site water-tight. If the sandstone is exposed in the upper bed of the stream for any distance the whole project may have to be abandoned. It would be practically impossible to prevent leakage without enormous expense, unless the valley was deeply covered with stiff clay or silt.

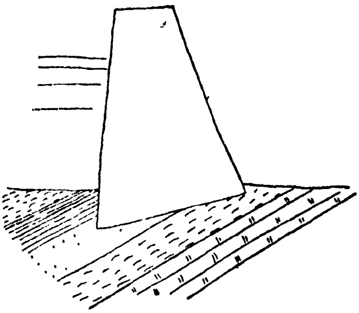


FIG. 49.
Dam on strata with upstream dips.

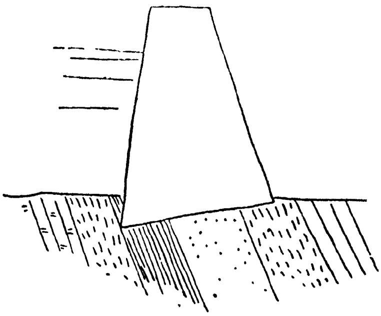


FIG. 50.
Dam on strata with high dips downstream.

DAMS PARALLEL TO STRIKE OF BEDS.—Among the bedded rocks it is obvious that the length of a dam should, if possible, be sited parallel to the strike of the bedding, and that the foundations be so laid as to have an apron of an impervious bed under the edge of the dam. If the beds strike parallel to the length of the dam and there is a choice of two sites, one with the beds dipping up-stream and the other with down-stream dips, it is generally preferable to locate the dam on rock with up-stream dips. In Fig. 49, an ideal cross-section of such a case is shown. The dam is represented as having an impervious bed as an apron on the up-stream side. The geological features of this section are excellent. Fig. 50 shows a dam situated on steeply inclined strata with down-stream dips. An impervious bed is depicted on the inner side of the dam. The structural features are good. Fig. 51 is a section of a dam on strata with low down-stream dips. A bed of shale is shown on the inner side of the dam, while a band of sandstone supports the greater part of the weight of the dam. The site is good, although inferior to the

two previous cases. Fig. 52 is a section of a dam on an anticlinal fold. In this case the dam is built on the up-stream side of the fold so as to attain the ideal structure of Fig. 49. In the section represented by Fig. 53, the dam is shown on the down-stream side of the synclinal axis. There is a possible loss by percolation through the bed of sandstone which is exposed below the dam. If the dam were built somewhat lower down-stream so as to expose the sandstone on the

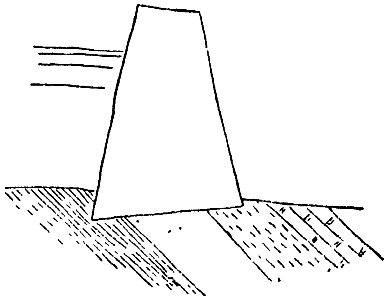


FIG. 51.
Dam on beds with low downstream dips.

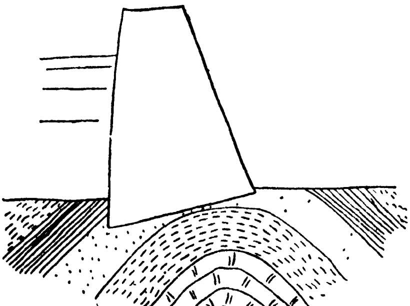


FIG. 52.
Dam on anticlinal.

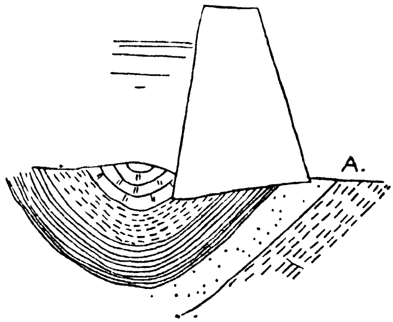


FIG. 53.
Dam on synclinal.

inner side, the site would be better chosen, because the percolation loss would be avoided and an apron of marl would be obtained.

DAMS BUILT OBLIQUE TO THE STRIKE.—If an engineer is compelled to build a dam across the strike of the rocks, he must locate his dam on the alignment which has fewest disadvantages and no serious defects. In such cases, the degree of dip, the number of possible percolation channels which cross the dam, the texture and condition of the various bands, become very important factors in making a choice. Each disadvantage of strike, texture, etc., becomes magnified in proportion to the height of the dam and may assume the degree of a defect. No serious defects can be permitted in high-pressure dams.

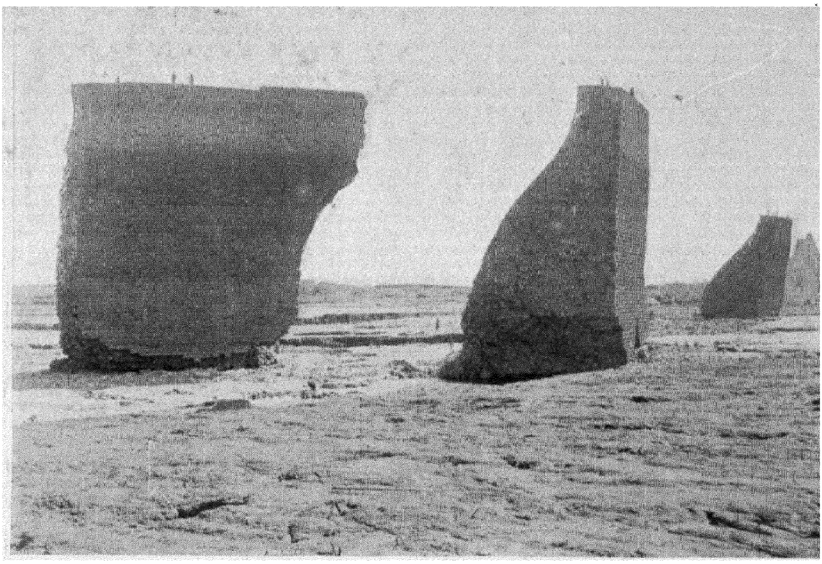
When the dips of massive bedded or banded rocks are gentle and the strike of the beds is slightly oblique to the length of the dam, there may be few bedding planes through which water can find its way under the dam. On the other hand, if the rock is laminated and the beds vertical with a strike transverse to the dam, there will be numerous planes along which water may percolate. If, in addition to these possible channels of infiltration, some of the beds are of a porous texture, it is evident that further leakage will take place. However, in ordinary storage dams, the porosity of fine-textured rocks, such as fine-grained sandstones and certain types of schist, should not be treated as a defect for which a dam site should be condemned; and, more especially is this true when the rock is free from open fissures. The most common cause of leakage from reservoirs is through open-joint planes and other fissures.

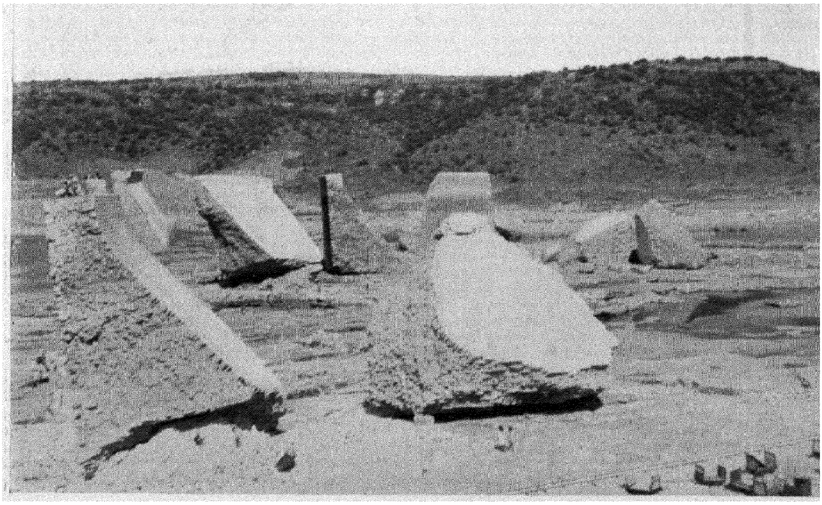
A very instructive example of a dam failure occurred in India, in 1918. The dam concerned was about a mile long, arched against the impounded water to a radius of 11,500 feet, maximum height 85 feet, and of gravity section. It was constructed of first class sandstone masonry (145 lbs. per cubic foot) in 12 inch courses with a hearting of sandstone rubble. It was designed to discharge the surplus water over the top.

The breach was 1,300 feet across in the deepest part of the river bed. An extraordinary spectacle was presented by the dam after the disaster. Complete sections of the dam, varying in length from 100 to 200 feet, stood facing in different directions below the breach—having been pushed bodily and swung round by the force of the rushing flood (see photographs XVII, A and B.)

The masonry on either side of the breach was torn away at a slope of about 1 to 1 from the bottom outwards. The top—15 feet—was displaced horizontally by shearing. On one side the face-work was torn from the hearting for a length of 200 feet. Many of the face-stones had been sheared off as if cut with a knife. Except in a few places, where excavations had been made and filled up to ground level only under the dam itself, the dam foundations were not more than 15 inches to 2 feet deep in the exposed rock of the river bed. Further, the foundations do not appear to have been "benched" to counteract the down-stream dip of the strata. It is also to be noted that no 'water-cushion' had been provided for the protection of the down-stream toe of the dam.

At the breach the surface of the rock was stripped and torn off by the rush of the liberated flood. The rock is a bedded sandstone in layers about 3 feet thick interbedded with thin sheets of shale (clayey sandstone). The strata as a whole has a low dip downstream.





A FAILED DAM.

Views show isolated sections of a dam which did not have sufficient grip of its foundations and was consequently pushed downstream bodily when the reservoir filled.

THE TIGARA DAM, GWALIOR (1919).

[*To face page* 232.

As exposed after the disaster, the rock is hard and difficult to excavate, but jointed. In the damaged sections, vertical cracks and fissures were everywhere evident in the disturbed beds.

The dam gave way on the first occasion of its being subjected to the full pressure of water it was designed to hold. Previous to this, temperature cracks had been observed in the dam. These cracks opened out in winter and closed up in the summer, and it was a section of the dam between two such cracks which first parted and drifted downstream. When the dam breached, 5,500 million cubic feet of water was let loose. The level in the reservoir fell 25 feet in the first hour and the impounded lake was entirely discharged in 6 hours. Timely warning had been given, and, although the flood spread over 96 miles of country and did considerable damage, few lives were lost.

Sir Michael Nethersole is reported to have given his opinion as an engineer that the failure was primarily due to the upward thrust of water under the dam, the water finding access beneath the horizontal layers of rock through vertical fissures; the secondary causes were ascribed to shallow foundations and shock of the overflow at the downstream toe. Another experienced engineer, Mr. C. B. Pooley, considered that the dam actually failed by sliding on its foundations but that this movement was caused by the upward hydrostatic head exerted from below, *i.e.*, to the primary cause advanced by Sir Michael Nethersole.

Sir Michael Nethersole's recommendations for reconstruction were as follows:

(1) Section of dam to be made thicker with a batter of 1 in 15 on the upstream face.
(2) Foundations to be 5 feet into sound rock on properly prepared bed.
(3) Cut off trench (depth H/6, H equals depth of water to be impounded) to be provided along upstream toe.
(4) Waterproofing of all fissures on upstream floor up to a distance H from face of dam.
(5) Depth of surplus discharge over dam to be reduced by allowing overflow to cascade over the full length of the dam.

From a geologist's point of view it would seem that the original dam was faulty in several ways. The foundations were obviously poor to an alarming extent. The use of sandstone masonry, with a facing of more impervious rock, rendered the dam liable to severe leakage after the "temperature cracks" appeared. However, it was a lesson, and is a useful example.

In view of the extreme caution that has been advised regarding the final selection of a dam site, it is interesting to look into the details of the site upon which the much talked of Aswan dam was founded.

This dam, built between 1898 and 1902, is of granite masonry and has a length of 1,996 metres, a height above low water of 24 metres, and is capable of impounding 1000 million cubic metres of water. It is designed to supply inundation canals with the flood waters of the Nile.

The alignment of the dam lies between two converging faults, and, upon the wedge-shaped mass of rock which has been let down (at least 18 metres) by these faults. Moreover, the length of the dam crosses several minor faults. The question of leakage through these fault fissures is evidently not of prime importance in this type of dam, because it is intended to deal only with flood waters; but there is the possibility of further earth-movements along the fault planes which may damage the structure.

The geologist responsible for the final selection of the site gives the following answer to this searching question. He says that:

"although the possibility of such movements cannot be denied, yet there is no evidence that they are taking place in our own day, and there is no reason to fear any continuous slow movement. Should an earthquake of any magnitude take place, a shift would occur more easily on the existing planes of weakness than elsewhere; but it is probable that a shock powerful enough to produce such movement would in any case damage the structure even did no faults occur."

The old bed of the river can still be seen close by the site of the dam:

"the highest part of the old Nile course lies about in the eastward prolongation of the line of the Aswan dam, which is itself built across the stream at the greatest throttling of the waters . . . this highest point is on the upthrow side of a fault, and the wedge-shaped mass previously mentioned occupies such a position, that if it were raised up through a height equal to the throw of the fault (18 metres) or perhaps a few metres more the Nile could be turned back into its old channel, and the cataract as we know it now would be dry except in high floods. The fact that if the motion, which has taken place at these faults could be reversed so as to bring the rocks into the same relative positions as they occupied before the faulting, the river would certainly follow its now dry channel, leads almost irresistibly to the conclusion that the faults must have changed the river's path. It follows, if this be accepted, that the faults belong to the Quarternary and not to the Tertiary period, and are thus amongst the youngest faults known in Egypt."

In other words, the erection of the Aswan dam was of necessity something of a gamble, but more than 30 years have gone by since the risk was accepted by the engineer, Sir William Wilcox. The dam has paid for itself over and over again. It has been increased in height and this provided for larger storage which has (1934) just been the means of saving the Nile Valley from serious floods.

Perhaps a bigger dam than that of Aswan is the newly (1934) opened Stanley dam at Mettur on the Cauvery. The following extract is taken from *The Statesman*, Wednesday, 22nd August, 1934:

"Now, however, once again the Nile is thought of in connection with India's rivers, for whenever any large irrigation scheme is planned or completed in this country the inevitable comparison is what engineering ability has done at Assouan. Probably for every person outside India who has heard of the Cauvery a hundred have heard of the Nile. That is because of the annual flood, the crocodiles, and Moses, pictuesque phenomena all. Yet the Cauvery can put up a much worse than respectable flood at times—there have been three of calamitous dimensions in recent years—and now it is able to boast of controlling works that leave those at Assouan well behind.

"Rivers in India are not all tidy instruments. Not many of them are content just with carrying water from mountain to sea. They love to spill it on the way when they have an abundance, to damage while they enrich the lands they flow through. They do not restrain themselves, and they must be restrained if they are to be as serviceable as they should be. Not one drop of the Nile, said Napoleon a hundred and fifty years ago, should be allowed to reach the sea; every drop should be made to serve the needs of a thirsty land. Assouan and its works are the realisation of his vague dreams. And the Stanley Dam and Reservoir, as they are to be known, are the embodiment of more than a century of thought about training and subduing the exuberance of the Cauvery. . . . It is expected that some 60 per cent. of the Cauvery's flow will be made available for irrigation, a proportion nowhere else utilised, we believe, except in Egypt. . . . A proper water supply will be assured to the age-old deltaic irrigation system over a million acres. Further, it will facilitate the supply of electric power, and defend the surrounding country against excessive flooding. Three times in the last twenty years floods have done wide damage. There is to be no more of that.

"The immediate interest is to control the water so that there may be irrigation but not flood. The Stanley Dam, nearly three times as long as the famous Assouan Dam, is 5,300 feet long, 176 feet high, 171 feet wide at foundations, 20½ feet wide on top where there is a 16 feet roadway. The cubic content of the dam is 54.6 million cubic feet, the biggest block of masonry in the world. The reservoir has a capacity of 102,000 million cubic feet, extends 34 miles upstream to the Mysore frontier, has an area of 60 square miles, and serves a catchment area of 16,300 square miles."

MATERIALS USED IN BUILDING DAMS.—There are two portions of a dam which must be built absolutely water-tight; one is the floor or sole of the dam and the other is the face of the dam towards the impounded water. The floor of the dam, perhaps it is unnecessary to say, should adhere so strongly to the rock of the foundations as to be virtually part of it. It is imperative that no water under hydrostatic pressure should enter below up into the body of

the dam. Loss by leakage is not the only factor involved in such cases; a more important factor is that the weight of the dam is diminished by the upward component of the water pressure. This may cause the resultant thrust on the dam to become sufficiently tangential to cause the dam to collapse by overturning.

In masonry or concrete dams which are backed with porous materials, there may be an advantage in allowing this porous back to become wet by permitting water to soak into it from the top of the dam. In time, the water percolates down and thereby increases the weight of the dam and improves its stability.

The materials used in building and the rocks on which high pressure dams are to be built, require careful consideration. The underlying rock and the masonry of the foundations must be strong enough to bear the weight of the dam and the thrust which results when water is impounded. The crushing strengths of the various types of rocks vary considerably (see table on page 77). It is generally difficult to cement the beds and joints of masonry in which great blocks are used. If these joints are open, they will function as channels for escaping water. For this reason, it would seem advisable to build with moderate-sized blocks and ensure the water-tightness of the jointing. By so doing the dam becomes similar in structure to a rock with cemented grains. The weight of the material of which a dam is built becomes of great importance in high dams. For example, a dam built of blocks of basalt will be heavier than one built of similar-sized blocks of quartzite, although both types of stone may be equally impervious. Furthermore, there is the consideration of the coefficient of linear expansion of the material to be used, especially in the case of a dam built in a country subject to great diurnal variations of temperature. Quartzite and other impervious types of sandstone have an appreciable thermal expansion; this may result in the development of vertical cracks in the dam which may cause not mere "weeping" but heavy leakage from the dam.

REVETMENTS.—Retaining walls, such as dock walls and revetments, are usually built to hold up loose soil or rock debris. The so-called angles of repose of these materials are, in general, not steep enough to prevent a pressure or thrust on the retaining wall. It is not possible to calculate exactly what this pressure may be, as much depends on the condition and nature of the material held up. (See "Applied Mechanics," Rankine, 21st Edition, 1921, pp. 212-221, 249-256; also Rankine "On the Stability of Loose Earth," *Philosophical Transactions* for 1856-7.)

The material supported by the revetment may be level with the top of the wall or it may be "surcharged" (see Fig. 54). In the

latter case there will be, other conditions being similar, a much greater thrust on the masonry or brickwork (see foot-note*) in consequence of which the wall must be more strongly built. It is well known that the surface slope (angle of repose) of loose materials varies not only with the type, size, and shape of the fragments or particles, but is very considerably affected by the degree of " wetness " of the material. For example, dry sand has a surface slope, or angle of repose, varying from 25° to 35°, while moist sand may stand for a time at 90° (*i.e.*, with a vertical face ; whereas, if sufficiently wet, the sand may be in

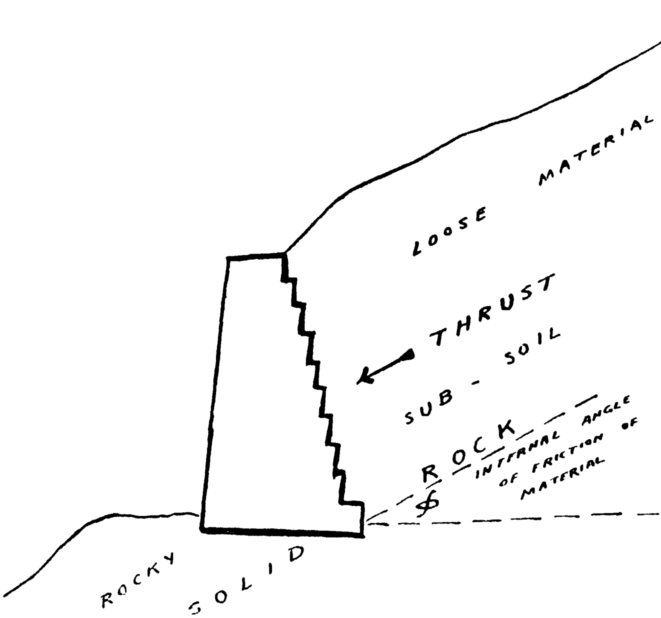


FIG. 54
Surcharged revetment.

equilibrium on a slop of 15°. This question is further discussed in the chapter on " Stability of Hill-slopes," under the phenomenon

* This is due to the pressure of the earth against the embedded face of the revetment (Fig. 54) being parallel to the surface of the bank, *i e.* inclined in a surcharged revetment and horizontal in a normal retaining wall.

The resultant thrust of the earth alone being :

(1) for a horizontal surface, $\theta = O$:

$$P_y = \frac{\omega x^2}{2} \quad \frac{1-\sin\varphi}{1+\sin\varphi}$$

(2) for a surface sloping at the angle of repose, $\theta = \varphi$;

$$P_y = \frac{\omega x^2}{2} \cos\varphi$$

If $\varphi = 30°$, $w = 100$ lbs., $x = 40$ feet, the ratio of the thrust in equation (1) to that in (2) is as

$$\frac{0.5}{1.5} : \frac{\sqrt{3}}{2} = .333 : .866$$

known as "creep" (*i.e.*, the gradual sliding movement of the soil and subsoil on slopes). In certain cases, surcharged revetments on hill-slopes have given way, not because they were not strong enough but because their foundations were not built on solid rock; they were involved in the superficial "creep" and consequently moved down the slope under the influence of their own weight plus the thrust of the material behind them.

The theory as to the pressure of dry earth at the back of a wall is that the force to be contended with is that due to the weight of the wedge-shaped mass included between the back of the wall and a line intersecting the angle between the vertical face and the natural angle of the material of which the earth consists. The greatest pressure results when the earth is so saturated with water as to be in a fluid condition (see "The Sea Coast" by W. H. Wheeler, 1902, pp. 92-93; see also Sir Benjamin Baker, *Min. Proc. Inst. C.E.*, vol. LXV).

The simplest formulæ for ascertaining the horizontal pressure against a wall having a vertical back where P = pressure, W = weight of earth (taken at 112 lbs. per cubic foot), H = height of wall exposed above the surface of the ground, Q = the natural angle of repose of the earth at the back of the wall, are:

(1) for mud pressure, $P = \dfrac{WH^2}{2}$

(2) for earth pressure, $P = \dfrac{WH^2}{2} \times \tan^2 \left(\dfrac{90^\circ - Q}{2}\right)$

(3) for earth pressure where a wall is infinitely surcharged,

$$P = \frac{WH^2 \times \cos^2 Q}{2}$$

The centre of pressure is taken as acting at $\frac{1}{3}$ the height of the wall measured from the bottom, and direction of centre pressure as normal to the wall.

Example H = 10 (height above beach).
W = 112 lbs. per cubic foot.
Q = 33.42 degrees.

(1) P = foot length of wall at $3\frac{1}{3}$ feet ($\frac{1}{3}$ height of wall).

$$= \frac{1 \times 10^2}{2} = 50 \text{ cwts.}$$

(2) $P = \dfrac{1 = 10^2}{2} \times \tan^2 \dfrac{(90 - 33.42)}{2} = \dfrac{100}{2} \times 0.14 = 14 \text{ cwts.}$

(3) $P = \dfrac{1 \times 10^2 \times \cos^2 33.42}{2} = 100 \times 0.345 = 3.45 \text{ cwts.}$

QUAY WALLS.—Under this title are also included those retaining walls which, besides functioning as revetments, are built to be partly submerged by water. They are generally constructed with vertical or steep faces in order to utilize the full depth of a limited water-way, as in canals, docks, etc. Although they act as a containing barrier between opposite pushing forces—the weight of the water and the thrust of the supported material—they may, as in dry dock walls, be required to stand the push of the loose ground alone. If the wall is built of porous rock, the contained material will become wet and its thrust will be greater when the water in the dock or canal is lowered; also, while a porous wall is partly submerged, its weight will be reduced by the upward pressure of the water. This aspect, *i.e.*, the mathemetical treatment of such walls, lies outside the province of the geologist who is chiefly concerned with the stability of the slopes and the choice of building materials.

Bruce on "The Kidderpore Docks" Calcutta; *Min. Proc. Inst., C.E.*, vol. CXXI, 1895, p. 98, gives information of considerable value.

The borings showed that the walls would have to be founded in sandy clay, and, when the first design was prepared, it was anticipated that a considerable quantity of water would have to be dealt with in constructing these foundations. It was then proposed to found the walls on wells, but this was unnecessary, as the ground below a depth varying between 10 feet and 20 feet from the surface was found to be entirely free from water, but when slightly moist it resembled putty and behaved much like that substance when the pressure was removed from above it. The sections of the cuttings in which it was first attempted to found the walls had side slopes of 2 to 1, and were carried down 10 feet below datum, the foundation being then built in a timbered trench carried down 22 feet below datum. The timbering of this trench had, however, only just been begun when the sides of the excavation slipped and the bottom of the cutting rose and destroyed the timbering that had been inserted. It was then decided not to carry the open cuttings lower than 3 feet below datum, as it was found that at that level there was less tendency for the ground to rise, and the sides of the cutting were thrown back to a slope of 3 to 1.

The walls are hollow above the foundations and built of brickwork throughout.

Note on the Movement of the Walls, by J. H. Apjohn.

"Attention . . . was called . . . to the fact that there seemed to be some movement of the backing which had been filled in behind the east wall to within 2.4 feet of the coping-level . . . the east wall began to bend out and . . . the coping-line . . . advanced nearly 6 feet at one

place (7th October, 1890). During the night (9th October, 1890) the south-west wall had also been thrust out, the displacement extending over a length of 450 feet, and being at its maximum of about twice the amount observed on the eastern wall. Arrangements were at once made for filling the dock with water from the river.

The three forces to be considered are the thrust of the backing, the weight of the wall, and the thrust of the berm in front of it. . . It is probable that when the backing caused the movement of the walls it was exerting a force due to a slope of $7\frac{1}{2}$ to 1 (a slope of $7\frac{1}{6}$ to 1 equals an angle of repose of 8°), or in the case of the eastern wall 36.6 tons per foot of wall. To resist this thrust of 36.6 tons there was that due to the berm on the other side, 26 feet above the bottom of the wall, equal to not more than 8 tons per lineal foot—giving but little support. Calculations lead to the conclusion that the admission of water to the docks had entirely obviated the danger of further movement of the walls."

Amongst other recorded instances (C. Colson, *Min. Proc. Inst., C.E.*, vol. CXXI, 1895, pp. 117-118) of walls having moved in a similar manner and probably from the same cause—viz., defective ground at the back of and under the wall—might be mentioned the West India South Dock wall, which had moved forward in 1868, on a fine silt joint or bed in the blue clay upon which the wall rested (*Min. Proc. Inst., C.E.*, vol. XXXIV, p. 176; and vol. LXV, p. 189), and the East India Dock wall, which moved not only laterally but vertically, in consequence, it was supposed of a bed of sand under the wall being affected by some excavations for dock works about a quarter of a mile distant (*Royal Engineer Institue Paperts*, vol. IV, 1880, p. 15). The walls of the Southampton Tidal Dock, founded on clay, had slipped forward 23 feet on a length of 400 feet in spite of every precaution in removing the mud at the rear and in filling the backing, (*Engineering*, vol. LVIII, p. 309 and *post*, pp. 125-127). At the Avonmouth Dock, trouble had been caused mainly by a treacherous bed of sandy clay, nearly as soft as silt, which had been found to lie between the bed of clay on which the wall was founded and the compact sand-beds beneath (*Min. Proc. Inst., C.E.*, vol. LV, p. 14).

An examination of the strata proved by the boring at the Kidderpore Dock would have told a geologist four things:

(1) that the peaty blue clay would constitute a weak foundation;

(2) that the excavated material which was used as the backing would almost become fluid when wet, although deceptively hard when indurated in the sun;

(3) that a warning should be given of the probability of appreciable outward thrust at the base of the wall backing, due to an increase in volume (therefore swelling) of the stiff dry blue clays should they become wet; and

(4) that the pure sub-surface sand with broken bricks and lime would have made a concrete backing far superior to the material used.

PROTECTING WALLS, EROSION WALLS.—This name is used comprehensively to include those types of walls which are made to prevent the erosion of a bank or shore by a river or the sea. These walls may be built with vertical or gently sloping faces, and either at right angles, as in groynes, or almost parallel, to the direction of the water current, as in training walls.

At Peterhead, there is a quay wall resting on a rock base about 2 feet above low water. At a short distance from the wall the rock bed dips, the depth of the water increasing to about 30 feet; there is then a ledge of rocks 160 feet from the wall on which water shoals to 22 feet, after which it deepens again to over 50 feet. With waves of 4 to 5 feet in height, and when the tide is from 7 to 8 feet up the wall, the waves only rise and fall against the face of the wall and are reflected without delivering any perceptible blow. When, owing to the state of the tide, the water becomes more shallow, the waves drag on the rock floor immediately in front of the wall, and, breaking, deliver such a heavy stroke on the wall that the broken water is thrown upwards to a height of 100 feet. (Wheeler, "The Sea Coast," p. 13).

A groyne with a vertical face towards the current offers an abrupt obstacle to the scouring stream and may result in severe undermining by the current at the head of the groyne. Such groynes, unless exceptionally well constructed, generally prove unsatisfactory. On the other hand, if the up-stream face of the groyne is at a gentle slope, it acts as an "expending beach," and may prove most efficient. Although training walls offer little impediment to the flow of a stream, they may, if built with a vertical face, be undermined by the scour of the current; consequently, the foundations must be carefully secured or the exposed face protected with an apron of stone or similar material.

BREAKWATERS.—These sea-walls are usually built as a protection for harbours against rough seas. In calm weather they are subject to an equal push of water from each side, but their weight is reduced by the volume of water they displace. In heavy weather the seaward face of the wall is exposed alternately to heavy blows followed by the sucking action of the receding waves. If the breakwater opposes the full force of the waves with a vertical face, the incoming water-blow may be as great as 4.27 tons per square foot on some parts of the wall. This calculation is arrived at by taking a wave 10 feet high, and the depth of water where it breaks, in repose,

at 5 feet; the weight of sea water as 64 lbs. per cubic foot; the length of the wave as 30 feet; the velocity of movement due to the head of 5 feet as 18 feet a second; the weight of the water in movement, for 1 foot in width, would be $30 \times 1 \times 5 \times 64 = 9{,}600$ lbs. This equals 4.27 tons. The kinetic energy would be the product of 4.27 tons falling from a height of 5 feet, equal to moving 21.35 tons of material to a height of 1 foot, or a blow of 4.27 tons per square foot. Should the wall be constructed of porous material, the shock will be transmitted by the interstitial water to the sheltered side and compress any air there may be in the pore-spaces of the wall; when the wave retreats, it exerts a suction on the blocks which, with the expansive force of the air within the wall, may result in some of the blocks being drawn out of the wall. Further, the downward rush of the descending wave may seriously scour the toe of the breakwater. Re-entrant angles in plumb-faced breakwaters will merely intensify all these effects. These dangers may be reduced by building the breakwater to take a glancing blow; but, at the same time, it is necessary to avoid diverting the waves across the passage through which vessels pass, because they may not be able to enter during a storm.

An ordinary beach is the most effective protection against storm waves, because the force of the sea is expended in driving the pebbles up the beach.

The force of waves on a beach depends on the height of the wave, its length, and the velocity with which it moves. These factors are all governed by the depth of the water (in proportion to the cube of the depth in which the waves break), and, therefore, varies with the seaward slope of the shore. The flatter the beach and the shallower the water the less the eroding and transporting effect of the breaking wave. The steeper the beach the stronger the under-current towards the sea during shore gales, and, consequently, the greater the erosive and transporting power of the waves.

If the seaward slope is long and gentle, it is possible a ridge will be built up some distance from and parallel to the shore. This will result in a backwater or lagoon. The protecting ridge thus made by the waves is spoken of as a "storm beach dam."

For this reason, the ideal sea-wall would be one with a sloping seaward face composed of great loose blocks so arranged that they would successively follow each other up or down the slope when driven by the incoming waves or dragged by the receding seas. The nearest approach to this is the low seaward slope of a wall which engineers term an "expending beach."

EXPENDING BEACHES.—The Chesil Bank on the south coast of England in Dorsetshire, is one of the most famous of shingle

beaches. In his evidence before the Royal Commission on Coast Erosion, 1907, Sir Aubry Strahan stated that:

"This great shingle bank commences near Bridport and extends a distance of 18 miles to the isle of Portland where it terminates abruptly against the cliffs south of Chiswell. For the first six miles of its course it keeps in contact with the coast, but then for 8 miles maintains a beautifully even curve at a distance of 200 to 1,000 yards from the mainland enclosing between itself and the shore a shallow salt-water and brackish lagoon known as the Fleet. For the last two miles the beach strikes boldly out to sea to join itself to Portland. It ranges in width from 170 yards at Abbotsbury to 200 yards at Portland and in height from 22 feet 9 inches above high water mark at Abbotsbury to 42 feet 9 inches at Chiswell. From Abbotsbury it rises at the rate of 1 in 8,450, and from Wyke to Chiswell at the rate of 1 in 880.

"The shingle extends to a depth below water spring tides of 36 feet at Abbotsbury, 42 feet at Fleet, and 48 feet at Portland. The stones of which the visible part of the beach consists increases in size from Abbotsbury to Portland, but those lying below water mark diminish in size in the same direction."

On the landward side it rests on a floor of clay at a depth of 3 or 4 feet above low water spring tides (see also *Min. Proc. Inst., C.E.*, vol. XII, 1853, p. 520). The beach above high water mark is composed of loose shingle, which is constantly being shifted—the shingle below is held in a matrix of sand and grit which is almost water-tight. The beach material is being steadily rolled over itself inland. Every storm carries a certain amount of stone up to the top and drops some over to the other side—these do not get back. The pebbles are obviously travelling from west to east, although the largest pebbles are found in the extreme east, near Portalnd. This curious fact is accounted for by the argument that the largest pebbles offer the greatest area to the impact of the incoming waves, and, as these waves hit the beach obliquely, the large pebbles get readily sorted out.

It was evidently by watching the resistance offered to the sea waves by such a beach that Charles Kingsley wrote ("Westward Ho, chapter III):

"the pebble ridge, where the surges of the bay have defeated their own fury, by rolling up in the course of ages a rampart of grey boulder-stones, some two miles long . . . which protects from the high tides of spring and autumn a fertile sheet of smooth alluvial turf."

CHAPTER XII

BUILDING SITES

In the construction of valuable structures, such as bridge piers, etc., which involve the public safety, every conceivable engineering aspect of the design is most carefully investigated, with the result that the finished work is often deserving of public gratitude. The architectural design, however, frequently receives more attention than the suitability of the site to accommodate those structures. There is generally some latitude with regard to the final selection of the site for an important building, whether it is within the prescribed limits of a town or in connection with a project for building a new city. In other cases there is usually still greater freedom of choice.

Each site requires a thorough investigation of the nature and structural features of the underlying strata. In all cases, the rock must be capable of supporting the weight of the building which is to be built upon it. On sloping ground, it is essential to ascertain the stability of the slope. The presence or absence of faults should be established—particularly in areas subject to earthquakes.

ON ALLUVIAL GROUND.—The loads which can be safely borne by different kinds of material have been briefly stated in the chapter on Retaining Walls. The importance of suitably distributing the pressure due to the weight of great buildings is well known. In the case of the Victoria Memorial in Calcutta, great expenditure was incurred in constructing an elaborate concrete "raft" on which the foundations for the walls carrying the dome of this magnificent building were built. Some of the piers of the Hardinge (Ganges) bridge over the river near Paksey, between Calcutta and Darjeeling, are founded on wells which were carried down to depths exceeding 150 feet below low water level. In this case, the only serious criticism of the work has been that the wells were possibly sunk unnecessarily deep. A view of this bridge is seen in the frontispiece (1934), when great efforts were in progress to prevent the Ganges from changing its course and leaving the bridge isolated. The value of good foundations is, however, well illustrated in the leaning tower of Pisa. There, although the structure itself has obviously been strongly built and

well bonded, the foundations were not sufficiently secured, with the result that unequal settling became apparent. The sinking of the arch in Waterloo bridge (over the Thames), is probably due to scouring at the pier foundations by the stream. This action would appear to be aided by vibrational movements in the pier foundations transmitted through the arch by the heavy, rapidly-moving traffic on the bridge. The bridge is now (1934) in process of demolition.

Enough would have been said on this subject of foundations on hill slopes in alluvial ground were it not for the fact that within the limits of the County of London there are curious examples of failure. St. Paul's Cathedral is from time to time brought to public notice because of the weakness of its foundations. In other parts of the London district, particularly on the gravel slopes of the suburbs to the south of the Thames, there are buildings which have been involved in the subsoil creep and several houses have had to be " shored " up. Although sand and gravel are supposed to have definite angles of repose, these constants very with the dry and wet condition of the material. However, the expansion and contraction of the particles, caused by the diurnal variation of the temperature, induce a tendency in the loosened material to gravitate *en masse* down the slope. If, in addition to these influences, the bed of gravelly material overlies a sloping rock surface, it is evident that " creep " must occur, Fig. 15. It is, therefore, not surprising that the walls of several buildings in the area indicated are traversed by cracks due to this slow slide. If the walls of houses built on gravel slopes show cracks from such causes, it requires little imagination to picture the results of similar effects on large gas and water-mains, which are laid horizontally for considerable distances across such slopes. That they crack and leak occasionally, is to be expected that they do not give trouble more frequently is surprising, and, continuing the argument with regard to river banks with moderately steep slopes of similar material, it would seem evident that the same agencies must be at work. This gravitative movement is almost certainly accentuated by the thrust component of the weight of heavy buildings which may be built on such river sides, especially if the whole of the material and the buildings are daily jarred by the movement of heavy road traffic.

Such considerations would probably not be serious in the case of structures on beds of stiff clay, and will almost certainly be absent when the hard rock is exposed and used as a foundation (Fig. 16).

EFFECT OF SPRINGS.—The deep cracks which are seen on clayey grounds during hot dry weather, constitute excellent channels for the admission of percolating water into the subsoil. During heavy showers of rain a considerable volume of water may flow along

the bottom of these cracks and erode underground channels. If the rock below the soil is porous, the water will continue downwards and possibly reappear at a lower level as springs. This type of action is particularly destructive to cliffs which terminate level lands. There is a free margin, and the cracks in the clay surface along the margin of such cliffs will tend ever to widen and deepen, and, finally fall away in masses, leaving vertical cliffs behind for the destructive process to continue.

If the rocks in a cliff consist of strata with the dip of the bedding planes outward at a low angle, it is evident that the infiltrating water will lubricate the surface of a bed of soft impervious material, such as clay, and produce an increased tendency in an overlying mass of hard rocks, such as limestone, to slide forward. This phenomenon is a very common cause of landslips along coasts or scarps which are bounded by cliffs. The landslips of Lyme Regis and Axmouth were largely due to these causes.

ON SLIP SLOPES.—In the section on Hill sides, etc. (p. 179), it was stated that great slopes, on which there was an appreciable mantle of alluvial material or disintegrated rock, occasionally showed evidence of slipping on a large area. If the movements had been in progress some time, the physical features mentioned, in the case of Murree might possibly be evident to a trained observer. Fig. 17 shows the type and relationship of the several features which may be detected. A, is the main slip scarp, F, a subsidiary scarp (the equivalent of the *bergschrund* in a glacier), B, the flat subsided portion, C, the bulge (where *seracs* would accur in a glacier), H, H lateral scarps (in the position where longitudinal crevasses are found in glaciers).

The secondary scarp, F and flat B, indicate that the main slip is breaking into two. Such features may be obscured to a great extent by vegetation, in which case it will be evident that the slip is not active and it may be that movement has entirely ceased. In any case, it would be inadvisable to erect buildings too close to the edge on the top of scarps A and F, or to establish houses, etc., close to the scarp margins of the flats C and H. Light structures might possibly be unaffected if built in the middle of the " flats." However, such slips may begin to move again after many years, especially if the light woods which may cover them are cleared, or rain-water assisted to percolate into the ground at the head of the slip, *i.e.*, round the margin H, B, H.

The only methods of securing a slip which is on the move are, first, excellent drainage to run off the rainfall or snow precipitation, particularly above the steeper slopes ; and, second, pinning the debris by revetments along the toe margin below C. The expedient of boring

into the slip from above and endeavouring to cement parts of the floor by grouting has apparently never been tried.

EARTHQUAKES AND FAULTS WITH REGARD TO BUILDINGS.—The prevailing opinion is that earthquakes are the result of the dislocation which follows the release of strain in the rocks of the earth's crust. Faults are the planes along which such dislocations take place. A fault once formed continues to be a plane of weakness along which further movement is likely to take place. Several faults are known on the opposite sides of which the strata have been displaced by upwards of 1,000 feet. This relative movement has seldom taken place in larger displacements than 20 feet at a time, and generally, by a much smaller amount; it thus represents the accumulated displacements of countless small movements, and it is for this reason a geologist speaks of the growth of faults. The line of a fault is consequently an unsafe place upon which to build a stone structure of importance.

Some regions are particularly liable to earthquakes, and in these areas certain types of buildings are less suitable than others. Stone buildings built of large blocks of comparatively brittle rock are generally more liable to destruction than well-bonded brick buildings. There is more elasticity in the greater bonding and less inertia in the individual bricks in the latter type of structures when they are subjected to the rapid oscillatory movements of an earth-tremor. In the former class of buildings, the heavy individual blocks are liable to develop independent movements and may become separated and result in the collapse of the structure.

BUILDINGS IN EARTHQUAKE REGIONS.—Investigations which have been made subsequent to destructive earthquakes show that certain features are common in most cases. It has been ascertained that earth-tremors are seldom felt in mines; that buildings on hills, surrounded by deep valleys are less liable to damage than those on the main ranges; that structures on alluvial ground are more usually destroyed than those which are founded on solid rock; that arched structures and tall and heavy super-structures generally collapse sooner than light, low structures; that heavy blocks of stone are more easily displaced than well-bonded bricks, or well constructed braced wooden structures; that steel frames built over with reinforced concrete on solid concrete raft foundations are the least damaged by severe earthquakes.

Taking these facts into consideration, it would appear that the best type of structure in an alluvial tract which is subject to earthquakes, would be a massive raft foundation upon which would be built a brick, concrete, or well-bonded stone building with the walls,

floors, and roof well braced together, and no vaulted arches. If each building is not built in too many storeys, and all tall chimneys are avoided and the doors and windows kept as reasonably small as possible, the danger of damage will be reduced. Further protection will be gained by having a deep trench round the building. It is also possible that several such buildings could be shielded by surrounding each group by a deep encircling trench.

A good rock formation and sufficient bracing to impart practical rigidity to the building are among the most obvious requirements in earthquake countries. Heavy ornamental copings and tall chimneys are to be shunned, since they are prone to oscillatory movements which, reinforced by resonance, may lead to collapse. If a rock formation is not easily found, some amount of protection is given by digging trenches all round or on the side from which earthquake shocks usually come.

The following extract incidentally brings out the dangers of certain sites :

The Kulu Valley. (See "The Marches of Hindustan," David Fraser, 1907, p. 90.)

"This beautiful valley knows what trouble is. The earthquake which created so much damage in Kangra in 1905, was no less calamitous here. Twenty thousand people lost their lives in Kulu, and inestimable damage was done to property. Nearly every village is in ruins, and the signs of destruction are visible in every direction. The Kulu houses are built of loose stones, with a wooden framework on the top. On this a ceiling of heavy flat stones is laid loosely. In the earthquake, which occurred early in the morning, these stones were shaken down on the unfortunate inmates, whole families being crushed like flies. . . . Colonel Rennick's houses at Bajaora and Nagar were badly wrecked, and members of his family narrowly escaped with their lives. Curiously, General Osborn's house, which is perched on an enormous rock fixêd in the hillside, was absolutely unshaken, though, a hundred yards off, the pictures on Colonel Rennick's walls were swung outward and dashed back with there faces inward, while a grand piano was overturned."

In a valuable work ("Building Structures in Earthquake Countries," 1912, Charles Griffen), Mr. Alfredo Montel records his experience of Italian earthquakes and gives the opinions of Japanese investigators. As the effects of earthquakes have perhaps nowhere been so elaborately studied as in the seismic areas of Italy and Japan, the information supplied in the above book should prove of importance to engineers.

Montel deprecates the opinion that there are rotary or vortical earthquakes. He explains the twisted obelisks, etc., which are so often noticed, as being due to the plane of sliding being held at a point excentrically situated, thereby causing the mass above to swing

round instead of moving straight. He considers that the horizontal, to and fro, movement of an earthquake is the most important, though he admits of a smaller vertical, up and down, motion. The Omori and Mercalli seismic scales of earthquake intensity are fully given, (see also chapter X, page 168), and are stated briefly as follows :

Omori Scale (Japan)		Mercalli Scale (Italy)	
Intensity	Acceleration per sec. per sec.	Intensity	Shock
I	300 mm.	I	Instrumental
		II	Very slight
II	900 mm.	III	Slight
		IV	Perceptible
III	1200 mm.	V	Strong
IV	2000 mm.	VI	Very Strong
V	2500 mm.	VII	Most strong
VI	4000 mm.	VIII	Ruinous
		IX	Disastrous
VII	greater than 400 mm.	X	Most disastrous

The duration of greatest movement (the most violent period), is generally from 4 to 10 seconds, although in very severe earthquakes it may be as long as 30 seconds (Japan). In the case of the Bihar earthquake (1934), the vibrations continued strong for more than three minutes.

With regard to the location of buildings, he says :

" Experience teaches that solid and compact soil ought to be selected ; in the plains as well as in hilly country buildings are safest on such ground.

Avoid heterogeneous and friable soil, especially if it is of little thickness and on a steep incline.

Avoid the vicinity of rivers, canals and interruptions due to geological causes, such as crevices, etc.

Avoid also bases of declivities and, in general, changes in the inclination of the soil.

Avoid soft, pasty, marshy ground, also filled up and embanked land.

Avoid also the immediate neighbourhood of the sea or of lakes, on account of the agitation of the water by the earthquake."

Discussing the choice of materials for buildings, he advocates the use of timber although drawing attention to the danger of subsequent fires. He is not attracted by iron structures and recommends brickwork if well bonded and of good, correctly-burned bricks. He deprecates heavy blocks of stone ; although masonry, if the blocks

are small and set in strong mortar, may be used; he strongly recommends, however, reinforced concrete. He discusses in detail, the importance of lightness and rigidity and directs attention to the use of tapering (parabolic) walls in order to avoid the development of an inverted pendulum motion.

Mention is made of the so-called "Free Wall" building, in which the walls are quite separate and can vibrate without impediment. He states that in such buildings the brickwork which fills in the empty spaces at the angles must become detached as soon as the walls begin to vibrate. Also, that there is the possibility of the walls becoming displaced with regard to each other and thus ruining the building. However, such structures could be adopted for railway stations, large workshops, sheds, etc.

The most suitable type of dwelling house is that known as the "Monolith" building. In these buildings the main walls are so bonded and knit together as to behave as a single unit. Such structures should be low in height; approach a circular plan; have free, indeformable roofs in order to avoid increasing the bending movement of the walls; contain few and small doors and windows; have light floors with protruding girders; partition walls, not to be joined to the main walls, so as to allow of free vibration; having winding staircases as they appear to be most satisfactory; balconies and towers to be avoided as well as tall chimneys, and vaulting not to be used.

"The repairing of old houses for the purpose of giving them greater seismic stability is generally not satisfactory. Experience proves that during an earthquake the old and the new are torn asunder."

PIER AND DAM FOUNDATIONS.—Certain aspects of this subject have been discussed in the Chapter XI on Retaining Walls. However, there are certain considerations which may be better explained here. In the case of piers, the chief essential is that the weight of the structure can be safely borne by the rock on which the foundations are established, or at least; that the pier will not sink if built on "wells" in deep alluvium. Two forces are concerned—weight downward, and reaction or friction upward. With dams or revetments, three forces are concerned—the weight of the dam or wall, the thrust of the impounded water, mud, or debris, and the resistance (to slide) offered by the friction between the floor of the dam and the bed upon which it has been founded. There are other factors which are very important, especially in the case of dams or piers founded in the deep sand and gravel in the beds of large rivers—one being the tendency of the upper part of the incoherent material to travel slowly downstream *en masse*.

This point is mentioned by A. L. Du Toit, in his paper on "The Geology of Dam Construction." He says, speaking of a narrow, deeply-buried chasm at the entrance of the Buffalo River Poort and found to be filled with sand and boulders to the amazing depth of 100 feet:

"it has been verified that under the pulsating drag of flowing water such saturated stuff can actually move bodily down stream; at Hartebeestpoort for example this action must have extended downwards to the depth of over 20 feet at least during an exceptional flooding in the Crocodile river."

The idea of founding a dam on such material is absurd, and it is equally wrong to think of establishing a bridge pier in such a place, unless the foundations are to be carried down to the rock below.

In my opinion there is yet another factor which becomes, or may become, operative in the case of a bridge used by trains or heavy motor traffic: this is the vibration which must be transmitted to the foundations of the piers. If the foundations are insufficiently deep and embedded in sand and gravel and not securely founded, a pulsating action may develop by resonance to such an extent that the pier foundations are loosened. In consequence of this, the natural scour round the piers may reach far down and partially undermine the pier foundations, thereby, causing the superstructure to sink down or push downstream. The movement may be exceedingly slow and only become appreciable after a period of years. Some such action may possibly account for the sagging which has made itself evident on Waterloo Bridge.

FLOOD DAMS.—Another reason for the selection of a particular site for a dam is that of dealing with excessive floods. Such an example is represented by the Stanley dam of the recently opened Cauvery-Mettur project. A brief description being as follows: Situated on the Cauvery river in South India, Mettur (11 48′ N. 77 48′ E.) is now the site of one of the great reservoir dams of the world. A general review of the project appeared in *The Engineer* (Vol. CLVIII, No. 4103) of 31st August, 1934, from which these notes have been taken. The idea of placing a dam across the river was an old one, but the scheme was sanctioned in 1925 for a site a mile upstream from that originally considered. The change was due to a flood in 1924, which discharged 470,000 cusecs as against a maximum of 250,000 cusecs of the previous 70 years records. The site now fixed permits of dealing with excessive floods. The dam is designed to serve a threefold purpose:

(1) To impound the flood water during the S.W. monsoon, thus making possible a regulated supply during the rest of the year.

(2) To serve as a flood moderator, so preventing damage to the country south of the reservoir.

(3) To utilise the head of water induced in the lake for hydro-electric purposes, the estimated supply being 10,000 h.p.

The scheme carried out by Sir (then Mr.) C. T. Mullings is based on that prepared by Col. W. M. Ellis, R.E., in 1910. This aimed at making a masonry dam, but as the methods were likely to be slow it was decided to build the dam entirely of Portland cement concrete—a decision which had to be modified later as will be explained. The extent of the waterspread is estimated at nearly 60 square miles. The capacity of the reservoir is computed at about 93,500 million cubic feet or roughly 600,000 million gallons. The dam is nearly a mile long and 340 feet above foundations with a cubical content of 54 million cubic feet. The total project cost nearly £6,000,000 sterling (about 8 crores of rupees), of which the dam represents £3,800,000 (5.09 crores of rupees). About 180,000 tons of Portland cement at Rs 53 per ton at site were supplied by the Shahabad Cement Co., Ltd., from their works at Shahabad in Hyderabad State. The cost of the cement alone is thus over £720,000 (Rs 95.4 lakhs). For purposes of economy the cement was mixed with 20 per cent. powdered brick or so-called Indian *Surki.*

The foundations of the dam are on Charnockite—a rock which when fresh is probably stronger than Aberdeen granite and possessing a similar texture. There is a good variety of this rock across the Cauvery valley at the dam and exposed in the river bed. Although the rock is stated to provide excellent foundations, particular care was taken to test its soundness by drilling. Where any soft material was disclosed cement grout was pumped under high pressure, and in the more extended occurrences of decomposed rock its removal was made by deeper excavation. The explosive used was liquid oxygen (air) prepared at the site by compression to 3,000 lbs. per square inch and expansion—the air being liquified at − 190 C. The crushed Charnockite supplied the matrix for the concrete, while clean river sand was obtained from the river itself. Test cubes were made for ascertaining the strength and permeability of the concrete—which consisted by weight of 0.8 parts cement, 0.2 parts surki, 4 parts of sand and 8 parts of stone, and probably weighed about 170 lbs per cubic foot. Two towers were erected to deposit the concrete and were also used for lifting the blocks of stone used for the impervious facing. It had been intended to use less sand and stone in the concrete for the facing, but it was found that the concrete delivered by the chutes did not give the same percolation results as the test pieces the entire facing was constructed with masonry laid in cement mortar

(0.8 cement, 0.2 surki and 4 parts of sand). An analysis of the cement used, "Char-Minar" brand, by the Government Test House, Alipur, Calcutta, is given on page 114.

DOCKS.—When selecting the site for a great dock in an unfamiliar coast, the engineer may feel anxious with regard to the probability of a rapid local uplift due either to regional crust movements or to lack of isostatic equilibrium. There are certain well known places, coasts and embayments, such as the Arakan coast of Burma and the Runn of Cutch, where subsidence and elevation are known to have been relatively quick. In many other cases the movements have been exceedingly slow—Stockholm rising at the rate of 18 inches in a century, the temple of Seraphis, near Naples, showing a movement down of 21 feet and a subsequent uplift of 26 feet, etc. If, therefore, seismic areas in which movement though small, is frequent, can be avoided, there is little fear, as a rule, that great regional elevation will affect the normal life of a dock. Provided the foundations are secure and the thrust of the wet mud behind the wall can be held, the building of a dock on a carefully chosen site can be safely proceeded with.

SITES OF CITIES.—Before closing this chapter mention must be made of some historical examples of cities, which have been discovered by exploration, of so ancient a period that no written record of their position is known; or of cities which, once well-known, were so overwhelmed by desert sands or volcanic debris that their sites were completely lost for a long time; and also of important cities which have disappeared so completely that even their exact location is in dispute. In the first category come the ruins of a city near Mohendro Jaro in Sind, which, according to Sir John Marshall, indicates a Sumerian people. The second case is that of Pompeii, which, although partly destroyed by an earthquake in 63 A.D. and rebuilt, was so completely overwhelmed by the dust and liquid mud from the eruptions of Vesuvius in 79 A.D. that it was completely lost until 1748, when it was accidently discovered by a peasant's well. In the third category are included examples like Capernaum, the proud Galilean city, which has so completely vanished that its very site is now not exactly known. For a city which is situated in an excellent position nothing short of a volcanic eruption is required to obliterate it. Earthquakes have ruined many towns since Pompeii —*e.g.* Charleston, Lisbon, Naples, San Francisco, Shillong, Tokio, etc. to mention only a few—but they have been reconstructed and flourish to-day.

There are other causes which appear to have fatal results on the life of cities. Rome was sacked and burned, but still survives because of its excellent location and the richness of Italy in produce and popu-

lation. On the other hand Nineveh never recovered from the blow she received from Babylonia in B.C. 600, and Babylon faded after its spoilation by the Median hosts 100 years later; the Macedonians revenged themselves on Persepolis by the heavy hand of Alexander; these and others are ruined places to-day only of archaeological importance. The dry climate of the areas mentioned has helped to keep the ruins in better preservation than would be possible in a damp tropical country such as parts of India and Central America. The Great Pyramid at Ghizeh, near Cairo, was built by the caprice of the tyrant Cheops about B.C. 3,000. It is perhaps the most enduring of all human monuments due to the dryness of the climate and the massive character of its construction. It stands 450 feet, has a base 760 feet square, occupies 13 acres and consists of 85 million cubic feet of huge blocks of stone which were cut and carried from a considerable distance. The details of its structure are claimed to have a prophetic significance to some Christian believers, but as a useful engineering work it falls short of the elegant Roman aqueduct of Pont du Gard, Nîmes (Nismes). These examples are intended to show that the slow processes of nature produce far less influence on well chosen sites than the changes induced by human spoiliation or incapacity. An earthquake may, as indicated, ruin a city, but if the site is good and the country rich and the people virile, the damage is rapidly repaired. In fact it requires nothing short of a volcanic eruption to bury a city and so stop its progress, or its deliberate raising to the ground by an invader, but even then it is necessary to render the people impotent at the same time.

THE SUEZ CANAL.—It is known that a navigation canal joined the Nile delta to the Red Sea in the time of the Pharoahs, and it is believed that a Phœnician fleet passed through this canal and circumnavigated the African continent. There is no mention of this canal in the time of the Exodus, but it may have influenced the first stage of this Hebrew emigration. The canal was, however, cleared and put into use about B.C. 450, when the Persian rule in Egypt was at its height, but it evidently fell into disuse after the Persian withdrawal. The channel was once again cleaned of sand and rendered navigable about 700 A.D., when the enthusiastic Moslem conquerors carried Islam across northern Africa. Little trace of this canal now remains, but Ferdinand de Lesseps was following human tradition safely when he formed the Suez Canal Company in 1856 and had the canal formally opened in 1869. It cost nearly £30,000,000 as against the £75,000,000 spent on the Panama Canal. It is a necessity and was declared exempt from blockade and free to warships of all nations by the International Convention signed in 1888. It is roughly 100 miles

from Port Said to the ancient trade city of Suez at the present head of the Red Sea. The depth of the channel is not less than 33 feet, and the width is being made to a minimum of 145 feet. The highest elevation of land encountered on the alignment was 52 feet above sea level a little north of Ismailia.

In the 75 years or so of its life as an engineering work constant attention has been given to the question of keeping the channel clear and of widening it. The subject of a slow regional uplift can be simply dealt with here, as a good deal of anxiety was evidently felt about the matter at one time. It is clear that the land routes south of Port Said have persisted since before the time of Abraham (B.C. 2126), and that subsidence has kept step with sedimentation in the region of the Nile delta. Thus the question of a rise of the land concerns only the southern part of the canal zone, *i.e.* from the high ground north of Ismailia southwards. According to available information, the Red Sea extended as far north as Lake Timsah at the time of the Israelitish exodus in B.C. 1491, and it is the popular belief that the crossing was made at about the latitude of the Serapeum of to-day, *i.e.* the tract between the Great Bitter Lake and Lake Timsah. According to Sir William Dawson, the Hebrews passed through the sea at what is now the narrow part between the Great and Little Bitter Lakes—roughly the position of Kabret. Dr. H. Clay Trumbull was of the opinion that the passage was effected directly from Suez to the Arabian shore. In each case the influence of a strong wind in disclosing a fordable crossing is accepted. The point at issue is that the sea has evidently retreated from near Lake Timsah to Suez, due to a rise of the land, since at least B.C. 2126, *i.e.* 4,060 years ago. The amount of uplift is known to be less than 52 feet. Thus taking the figures given, the rise could not exceed one inch in 6.5 years, and is less. Dredging operations can safely attend to this amount if the rise is maintained in the same very gradual manner.

PART III

WATER - SUPPLY

CHAPTER XIII

GENERAL RAINFALL CONSIDERATIONS

METEOROLOGICAL ASPECTS.—Although the atmosphere consists essentially of a mixture of one volume of oxygen to four volumes of nitrogen, it also contains small quantities of carbonic acid, dust, and water-vapour.* This water-vapour remains invisible in the atmosphere until the air containing it becomes saturated with moisture. The formation of clouds, mist, snow, hail, and rain, show that the saturated temperature has been attained. The water-vapour is obtained by the evaporating influence of warm currents of air which blow across the surfaces of seas, lakes, rivers, marshes, etc. Saturation and condensation are caused by these moisture laden winds rising and cooling against mountain ranges. The condensed moisture is largely precipitated as rain which flows into the streams and rivers, and, eventually back to sea. Thus, it is seen that the water of the earth's surface is kept in ceaseless circulation by the energy of the sun's heat and the gravitative pull of the earth. The most important source of water, both from the engineer's and the geologist's standpoint, is rain.

ATMOSPHERIC PRESSURE.—The amount of water-vapour in the air is greatly affected by the temperature and pressure of the atmosphere. At sea level it is theoretically possible to balance a column of water 33.947 feet high against the pressure of the atmosphere. This works out to roughly the same as a column of mercury 30 inches high in a vacuum tube and which equals a pressure of

* The average composition of normal air may be taken as follows :

	Vols.
Nitrogen	769.5000
Oxygen	206.5940
Aqueous vapour	14.0000
Argon	9.3700
Carbon dioxide	0.3360
Hydrogen	0.1900
Ammonia	0.0080
Ozone	0.0015
Nitric acid	0.0005
	1,000.0000

Also :

Neon	0.000014
Helium	0.00000276

14.73 lbs. (avoirdupois) per square inch or about 2,121 lbs. per square foot. An atmosphere in the metrical measure is taken as the pressure of 760 millimetres (29.922 inches) of mercury at O° C. (32° F.) at Paris, and is approximately 1.033 kilograms per square centimetre. The British measure of an atmosphere is taken as the pressure of 29.905 inches of mercury at 32° F. in London and is about 14¾ lbs. per square inch or 2,124 lbs. per square foot. At low levels $\frac{1}{10}$ inches of mercury equals a height of, roughly, 100 feet of the air column; at elevations of 18,000 feet it represents 200 feet; at altitudes about 36,000 feet, 400 feet; and at heights of 60,000 feet, a fall or rise of $\frac{1}{10}$ of an inch of the barometer means a difference of 1,000 feet in height. It is well known that, as in the case of a gas which is allowed to expand in volume, there is a cooling down of the air as it rises and becomes rarified. It is not so well appreciated, however, that the converse also holds good and that the compression which is exerted on air which descends causes a rise of temperature. This effect is well illustrated on the case of the winds known as the Föhn on the Alps, the Chinook in the west of the U.S.A., and the Hangu breeze in N.W. India.

These winds descend from cold mountain regions and warm up 1° F. for every 320 feet of descent. They start cold, and are consequently low in their moisture contents. As will be seen presently, the increase in temperature, which they suffer under the increased pressure of the atmosphere of the lower elevations to which they descend, makes them drier and therefore capable of taking up more moisture. The Föhn has been known to evaporate 2 feet of snow in the Grindelwald valley in 12 hours. Perhaps the most astonishing example is that given by J. Hann in his " Handbuch der Klimatologie, Engelhorn, 1908-11." He says that at Kipps in Montana the temperature on the 1st December, 1896, was 45° below zero (—13° F.), and the ground covered by 2½ feet of snow. It was pasture land for winter feeding, and an ugly situation confronted the cattle farmers. Suddenly that evening dark, ragged clouds rolled over the mountains to the south-west, and a blast of the Chinook swept down. In the course of 12 minutes the temperature rose 36° and the snow disappeared.

AIR TEMPERATURE.—Air expands, or contracts, approximately .002 of its volume per degree F. Put in another way, the temperature of rising air cools 1° F. for every 324 feet of ascent, and, *vice versa*, the temperature increases 1° F. for every 324 feet of descent near the earth's surface. At high altitudes this rate becomes 1° F. for every 540 feet difference of height. On level ground the cold air remains more or less stationary; but on slopes, especially in valleys,

its greater density causes it to drain down the slopes. By so doing the lowest temperatures will be met with in the bed of the valley, and often a severe frost, sufficient to damage delicate crops, may be felt in the valley, while similar crops higher up the valley remain unaffected.

Very little of the sun's heat is directly absorbed by clear (transparent) air. The experiences of the Everest Expedition of 1921 in the icy air of the higher Himalaya were that sun-hats had to be worn to avoid sunstroke even while standing in thick snow. Some of the sun's heat is absorbed by the suspended dust particles, but larger quantities are taken up by the water-vapour, especially when it is present as clouds. By far the greatest heating effect on the air takes place by its *contact* with land or water surfaces which have been warmed by the heat of the sun's radiation.

A land (rock) surface, because of its smaller specific heat, warms or cools much more rapidly than a water surface. In the tropics the climate of a dry land region is always more bearable than a moist tract, while the slow cooling of water often makes life distressingly unpleasant in hot weather on board ship in such places as the Red Sea or Persian Gulf. There is little fall in the air temperature over large water surfaces in hot weather. When the air is clear the variation in the temperature near the ground of a given locality, especially in a desert region, may be very considerable. The temperature in the afternoon may be as high as 180° F., while the reading in the early hours of the morning may be as low as 32° F. These diurnal variations naturally affect the density of the atmosphere and cause diurnal variations of the barometer. To the same causes are to be ascribed the phenomena of land and sea breezes, " afternoon " winds, etc.

Sudden falls of temperature may cause a very rapid precipitation of rain if the air is damp. During a typhoon in the Phillipine Islands in 1911, the rainfalls on the 14th, 15th, 16th and 17th of July were 35, 29, 17, and 8 inches, respectively.

WHIRLWINDS, ETC.—It is generally agreed that although dust-storms, whirlwinds, waterspouts and tornadoes are the same kind of phenomena, differing only in their size, intensity or the degree to which water vapour is condensed, and that hailstorms and rainstorms are simply the manner of precipitation accompanying them, they are nevertheless quite distinct from cyclones. Cyclones are due to unequal densities or atmospheric pressures at the same level due to inequalities of temperature and humidity of the air over wide areas, while whirlwinds occur quite locally, due to vertical differences or disturbances of the atmospheric equilibrium whereby upward vertical movements of the air are produced. The largest tornado, although far more destructive in its effects, is small in ize (extent) compared

with a cyclone. Cyclones occur at all hours of the day and night, whereas tornadoes and whirlwinds show a distinct diurnal period.

The gyratory movement of whirlwinds, etc., produce the dust-storm or waterspout in a simple manner if the speed of the air is high enough. Generally a dark cloud covers the sky and a conical point extends gradually down. Beneath this point the dust is stirred or the surface of the sea ruffled and agitated. Finally the cone from the sky elongates into a column which touches the surface of the sea, and water is drawn upward to make the familiar waterspout. The column of cloud seen extending downward is not really due to the actual elongation of the cloud from above as the formation of cloud from the water vapour in the column of rapidly rotating air. In the case of a violent movement, a great waterspout may lift upwards, carrying light materials high into the sky from the sea. On land such air movements grow in intensity to become true tornadoes which, from the experience of sufferers in Ohio, Illinois and elsewhere in the United States, are capable of lifting buildings, breaking large trees, and travelling across the land at over 30 miles an hour. The tornado of 4th June, 1877, passing over Mount Carmel (Illinois) Methodist Church, swept off the spire, vane and gilded ball, and carried them 15 miles north-eastward.

Similar destructive storms, usually accompanied by rain and hail, traverse parts of the Central Provinces in India occasionally in an east-south-east direction. Like the tornado, they are restricted to narrow belts averaging a mile or so wide, sometimes more than twice this amount, and often less. The rotary movement is not always noticeable when the travel of the wind is great in a horizontal direction, but in the lesser dust storms it is quite clear. The fall of hail is due to the upward movement, which first causing a condensation of the water vapour, carries the water particles upward into cold air, so producing grains of ice. If these fall direct to the ground, it is a crystalline hail, but it often happens that the falling material is caught and whirled upward again and again, in which case the hailstones are usually of granular texture, or even composite, *i.e.* laminated with crystalline ice and granular ice. It is evident that with the whirling up the condensation of the water vapour may directly take the form of snow instead of rain and produce a snowstorm or more complicated phenomenon involving snow and hail.

HUMIDITY.—It has been experimentally determined that at 0° C. (32° F.) it requires 2.37 grains of water to saturate one cubic foot of air (about .08 lbs. in weight) with water-vapour. For 40° F. the amount necessary is 3.9 grains ; at 50° F., 4.28 grains are required at 60° F., 5.8 grains ; at 70° F., 8 grains, etc. A cubic foot of air at

62° F. weighs .076 lbs. (=1.217 ozs. or 532.7 grains) and 13.141 cubic feet of air at 62° F. weigh one pound. If the temperature is raised, the capacity of the air to take up more moisture is increased. A decrease in temperature results in condensation and precipitation of part of the contained moisture. Cold winds will, therefore, feel dry as they descend from mountains, and it is not rare to see clouds disappear as they roll down mountain slopes; on the other hand, it is a familiar sight to see clouds increase as they ascend from the valleys. From what has been said, it is evident that there is a definite temperature (the Dew Point) corresponding to the amount of water-vapour (Absolute Humidity) in the air at which saturation will occur.

There are few places on the earth where the air is absolutely dry. The apparently dry winds of a hot desert region often contain more water than the damp air, on a wet wintry day, in a cold climate; *e.g.* air at a temperature of 70° F., having an absolute humidity of 5.87 grains of water per cubic foot of air, will, if blown over a warmer land surface, feel dry and no clouds will be seen. On the other hand, if this same air encounters the cold slopes of a mountain range and has its temperature reduced to 50° F., condensation will take place and 1.59 (5.87 —4.28, see above) grains of water per cubic foot of the air will be precipitated as rain.

Elaborate tables have been prepared by the help of which, after taking the readings of a wet and dry bulb thermometer, it is possible to ascertain accurately the amount of water-vapour in the air and the saturation temperature of the place of observation.

EFFECT OF MOUNTAINS.—It has been estimated that

"half the moisture in the air lies below an altitude of 6,500 feet, three quarters lies below 13,000 feet. Therefore a high mountain chain is a very effective barrier to the passage of vapour" (*see* Physical Geography by Philip Lake, 1915, p. 110).

When a prevailing tropical wind blows from the ocean and encounters a great plateau scarp or a high range of mountains, the air current is forced upwards; the air expands and cools and, if the cooling is sufficient, rain will be precipitated. In most cases this rainfall will occur on the windward slopes of the mountain range. This is well shown in the case of the Surma valley south of the Assam plateau, where the monsoon blows northward from the Bay of Bengal and encounters the Assam hills (6,000 feet). (See table on next page.)

E. W. Vredenburg ("A Geological Sketch of the Baluchistan Desert and Part of Eastern Persia," *Memoirs Geol. Surv. India*, Vol. XXXI, Part II, 1901, pp. 212-213), in discussing the gradual desiccation of certain lakes of that regions says:

"It is one of the fundamental facts in physical geography that the

Normal Rainfall (inches)

	March	April	May
Assam (Brahmaputra) Valley	3.57	8.09	12.03
Assam (Surma) Valley ..	7.75	13.42	18.00
North Bengal	1.26	3.97	10.65
East Bengal	2.31	4.24	10.45
Deltaic Bengal	1.44	2.31	6.16

increased altitude of the land in mountainous regions causing the vapour-laden atmosphere blown from the sea to rise to higher and colder strata in the air, determines the precipitation of rain on the slopes of the mountains turned towards the sea. When the clouds reach the opposite slope they descend once more to lower altitudes and the air is no longer saturated. In this way the inland drainage area will never obtain enough moisture from the sea to repair its own losses, and its ultimate fate must in all cases become irrevocably its conversion into a desert."

The same writer goes on to say that in Baluchistan, since it has been under British Administration, there has been improved irrigation and a better employment of its natural resources.

" Where there used to be no cultivation, now, owing to an artesian well or a *káréz*, an artificial oasis has been created . . . but it must be remembered that the rainfall is ever decreasing, that it is the ultimate source from which all the water used for irrigation is derived, and that consequently the supply is gradually dwindling. Of late years *kárézes* have dried up at Quetta, which had given an abundant supply for more than a century, and this notwithstanding that the work is kept in perfect repair."

DISTRIBUTION OF RAINFALL.—In large engineering projects involving the utilization of rainfall, it is necessary to determine the various amounts of rainfall discharged into streams, or lost by evaporation and other causes, or which percolate into the ground. It may be essential to ascertain the rate of water percolation through various kinds of consolidated or unconsolidated strata. In many instances it is important to determine, experimentally, the capacity of wells. Most of this data is collected by the engineer. Without such information it may be quite impossible for a geologist to give an approximate estimate of the quantities of water which may be expected from a certain source in a given locality. It is needless to say that it is unsatisfactory, and generally useless, to assume that one-third of the rainfall goes into streams as run-off flow, another one-third percolates into the ground, and that the remaining third is lost largely by evaporation and absorption by plants and mineral substances.

Of the precipitated moisture, that due to direct rainfall is generally the most important factor in questions of water-supply and irrigation. The flow of streams which drain snow-fields and glaciers is sometimes of considerable importance. Part of the rain which falls on the surface of the ground is discharged into streams and drains away; some of the rainfall percolates into the ground, and either re-emerges in springs and assists the stream flow, or replenishes the so-called stationary underground water; the remainder of the rainfall is lost by evaporation to the air, or absorbed by growing plants, or enters into combination with the mineral substances in the soil and rocks. This proportionate disposal of the rainfall of a given country is modified by several factors. The more important of these factors are (1) the climate of the area concerned; (2) the nature and slope of the ground on which rain falls, and (3) the rate and duration of precipitation of rain.

One inch of water spread over an area of one square mile represents nearly 14 million gallons and has a weight exceeding 60,000 tons. It is evident from this that a normal tropical downpour of 4 to 5 inches in 24 hours means both a large volume of water and a considerable load suddenly applied locally. From this it is simple to conjecture a flooded countryside of great extent with the water at least 4 to 5 feet deep. Professor Milne has recorded that there is an appreciable lowering of the coastal tracts of Western Japan after heavy rain, but that the land rises again as the water runs off. And seismograph records have revealed that the west coast of Ireland sinks about 3 inches under the weight of the incoming tide and recovers again as the tide ebbs.

DESERT TRACTS.—In a hot, flat country not traversed by a prevailing wind from the sea, it follows that if local atmospheric disturbances are to produce rain, the absolute humidity of the air must be high. Any such condensation usually causes heavy local downpours, although the total annual rainfall will naturally be small. This is well shown in the examples taken from Rajputana, given below:

The average annual rainfall at Jodhpur, a city built on sandstone in a sandy open country, for the 26 years ending 1905, was 12.75 inches. This was roughly distributed as follows: June, 1.30 inches; July, 3.78 inches; August, 4.43 inches; September, 1.90 inches; and the remainder during the other months. In 1893 the annual rainfall was as high as 29.75 inches, while in 1899 it was as low as under 1 inch. The maximum precipitation in 24 hours was 10 inches in August, 1881.

No less interesting is the rainfall at Bikanir, a town in a wide sandy plain, where the average annual rainfall for 26 years ending 1905 was just under 10 inches. The fall of rain in the closing days of June was

1.28 inches; in July, 3.04 inches; in August, 2.63 inches; in September, 1.15 inches; and the remainder during the other months of the year. The average rainfall in 1892 was 18.84 inches, but only 1.14 inches for the year 1899. The maximum precipitation during a single day was 5 inches on the 30th August, 1874.

In other places, such as Aden or the lower Nile valley, the annual rainfall is practically nil; and yet in these places when rain does fall the downpours are so heavy as to cause devastating floods.

COLD DRY AREAS.—In this connection the following remarks on the Kohat region of the North-West Frontier Province of India are interesting:

"The district as a whole lies high, and the hot season, though oppressive, is short, and the spring and autumn months are pleasant. The winter is very cold, and a cutting west wind, known as the 'Hangu breeze,' blows down the Miranzai valley to Kohat for weeks together. The monsoon rains do not usually penetrate as far as Kohat, and the rainfall is very capricious. The average fall at Kohat is 18 inches, whilst the greatest fall since 1882, was 48 inches at Fort Lockhart on the Sāmāna in 1900-1, and the least 5 inches at Kohat in 1891-2. The distribution of the rain is equally uncertain, villages within a distance of a few miles suffering, some from drought and some from floods, at the same time." (*Imperial Gazetteer of India*—North-West Frontier Province, 1908, p. 169.)

AREAS OF HEAVY RAINFALL.—Perhaps no greater contrast can be imagined than the difference between a practically rainless region, such as Rajputana, and a tract having a very heavy rainfall such as the Assam hills south of Shillong. The average annual rainfall of four places in this area (Assam) is shown in the accompanying table.

Months	Shillong	Jowai	Maoflang	Cherrapunji Police Station
	34 years	30 years	14 years	28 years
January	0.49	1.07	0.87	0.74
February	0.81	2.04	0.69	2.16
March	1.85	6.30	1.93	11.08
April	4.29	10.46	4.81	32.24
May	10.06	26.18	11.41	51.53
June	16.46	66.15	32.11	105.12
July	13.48	43.94	30.00	109.49
August	12.79	34.74	21.10	76.50
September ..	14.75	31.66	19.26	53.25
October	6.23	12.69	8.73	13.97
November ..	0.98	1.44	0.47	1.49
December ..	0.25	0.75	0.28	0.23
Total for year	82.44	237.42	131.66	457.80

In 1861 no less than 905 inches of rain fell at Cherrapunji, of which 366 inches were assigned to July. The maximum precipitation in 24 hours was recorded in 1876, when 41 inches of rain fell on the 14th of June. This does not give a true idea of the rate of precipitation, because by far the larger proportion of the rain falls at night between the hours of 6 p.m. and 8 a.m., and the locality in consequence enjoys a considerable number of hours of sunshine. In 1853, 348 inches of rain had fallen by the 24th of August; of this quantity, 276 inches fell at night, and the remainder during the day. The area is much more free of mists than either Darjeeling or Mussoorie although these places have an average rainfall of about 120 inches and 90 inches annually. Falls of rain of from 3 to 4 inches in an hour are not rare in India, although few instances are recorded at the same station. Even in the British Isles falls of rain—$\frac{1}{3}$ of an inch in 2 minutes, 1 inch in 10 minutes, $3\frac{1}{2}$ inches in an hour—have been recorded. It is this rate of precipitation which is so important to the civil engineer. He has to be prepared for abnormal conditions rather than normal conditions when designing reservoir dams and discharge channels.

EFFECT OF MARSHES, FORESTS, ETC.—It has been experimentally determined that water-logged soils in general have a cooler surface than well-drained soils. In a tropical country, where rice cultivation is widely practised, as in Bengal, the surface temperature is therefore a little cooler than would be the case if the same tracts were well drained. The enormous evaporation from rice field areas, however, affects the humidity of the air, and must result in a greater precipitation of rain in hilly regions to leeward of these great marshy lands. Partly to such a cause is ascribed the prolongation of the south-west monsoon and the heavy rainfall on the Assam hills (Cherrapunji) which lie to the north-east of the great rice-growing region of Bengal.

The considered opinion of several qualified authorities is that forest-covered areas, besides producing a cooler climate, induce a greater rainfall than bare country in the same region. Other physical considerations being the same, the amount of percolation in forest tracts is less than in open country, so that the run-off flow percentage of the rainfall will be greater from wooded areas. E. T. Quale ("The Increasing Run-off from the Avoca River Basin" (due, apparently, to De-forestation": *Pro. Roy. Soc. Victoria*, 35 (N.S.), Part II, 1923, Art. XIV, p. 143) disagrees with this, and speaking of an area in Australia says:

"23 square miles is drained by the Avoca River. . . . Most of the basin has been in its present state for perhaps 20 or 30 years, but

within the last decade much clearing has been done on the slopes of Mt. Lonarch and Ben More, as well as on the Sugerloaf itself. On Mt. Lonarch the clearing is most noticeable, especially within the last five years, and amounts to perhaps two or three thousand acres. . . .

"The flow of the Avoca River is officially measured by the State Rivers and Water Supply Commission at the Coonover Weir . . . . If we compare the records for the twenty years, 1890-1909, inclusive, with those for the ten years, 1910-1919, we find that in the former period the river actually had no flow or ceased to run in 79 months; that is, there were 79 months during the whole or a part of which there was no discharge at Coonover Weir. . . . During the decade 1910-1919, the river has never ceased to flow. . . . A comparison of the two great drought years, 1902 and 1914, is equally instructive. Though the latter was more severe the river flow never fell below 5 cubic feet per second, whereas in 1902 there were seven months during which the river never ran at all . . . floods are extremely unlikely to occur in the summer months, and they reach their maximum frequency and intensity in August and September. The importance of the degree of soil saturation is made very obvious by the fact that the heaviest flood falls have not occurred in these months. . . The flood of January, 1897, was due to a fall of over 4 inches in one day. . . . The great flood of August, 1909, was due to a series of thunderstorms giving a total of 3½ inches in about 19 hours, with its heaviest downpours during the last hour over the head streams. The great flood of September, 1916, was due to 2.60 inches falling in 2 days."

"The official gaugings cover 32 years. These provide three decades, exclusive of the years 1920 and 1921. The first of these, 1890-1899, was the wettest, giving an average of 20.1 inches annual rainfall, and an average annual run-off of 59,278 acre feet. The next decade had an average rainfall of 19.4 inches, and a run-off of 44,230 acre feet. The last decade, 1910-1919, had a rainfall of 19.5 inches and a run-off of 74,439 acre feet . . . . the rainfall averages nearly the same as before but the run-off has increased by over 50 per cent.

This gain may be apportioned to the two main sources of increased flow (a) the amount gained by springs from the destruction of trees, and given to maintain a constant flow; (b) the increased run-off due to better drainage resulting from erosion of channels, silting up of water holes, formation of paths by stock, moisture condition of subsoil, quicker saturation of sub-soil due to killing of the trees, the raising of the water table, etc."

RUN-OFF FLOW.—Each of the factors—run-off flow, evaporation, percolation, etc.—may vary enormously. Rain which falls on bare hill slopes composed of impervious strata, *e.g.* slates, shales, etc., is almost entirely discharged into the stream courses, and passes down to the valleys as flood or run-off water. On the other hand, there is not likely to be much run-off from light intermittent showers which fall

on parched, level, sandy ground. H. F. Blanford ("The Climates and Weather of India, Ceylon, and Burma," 1889, p. 274) gives an example: at the beginning of the wet monsoon (June) a fall of 2.25 inches of rain in 80 minutes on the Ambajhari drainage area (4,224 acres) produced no appreciable run-off owing to the whole of the fall being absorbed by the desiccated soil. However, once a porous soil is water-logged by previous heavy rain, it will offer an impervious surface to subsequent showers. Thus it is interesting to record that on the same catchment, Ambajhari, near Nagpur, India, during the closing weeks of the monsoon (September), an almost identical fall, *i.e.* 2.2 inches in about 80 minutes, resulted in 98 per cent. of the precipitation flowing into the reservoir in 2 hours and 50 minutes. Observations made by Sir Alexander Binnie ("Rainfall Reservoirs and Water-Supply," pp. 28–32) in connection with the Ambajhari reservoir are worth quoting in detail:

Months	Rainfall in inches	Run-off flow in percentage of rainfall	Remarks (1872)
June	6.77	4.7	The Rains begin about 15th June.
July	12.70	22.7	
August	11.82	55.8	
September	7.99	74.4	
October	4.37	39.4	The Rains terminate about 15th October. In this case there was a spell of dry weather be-before the October rains.
Total of Season	43.65	40	

It must be noted that the Ambajhari catchment lies on basaltic lava flows. These volcanic rock-sheets are almost horizontal and slightly decomposed on the surface and well jointed internally. They are, however, often covered with an appreciable thickness of highly absorbent clay (*regur* or black-cotton soil), which cracks and crumbles after a period of long drought.

Examples have been given previously regarding heavy downpours in desert areas such as Jodhpur and Bikanir, and it was stated that although the soil was sandy and the annual rainfall small, yet floods frequently resulted from exceptional falls of rain. Dr. Alfred Bramwell, of the Imperial College of Science, London, has suggested that a heavy fall of rain possibly "traps" the air which exists in the inter-

stitial spaces between the sand grains. This would make the subsoil " air-logged," as he calls it and offer an impervious substratum to infiltrating water, thereby resulting in a large run-off of flood water. In the case of clayey soils, such as the black-cotton soil of the Deccan in India, there is little " air-logged " effect. On such surfaces moisture is drawn greedily down into the dry ground by powerful capillary action, and as the soil absorbs large quantities of water before becoming wet, there is very little run-off after short sharp showers.

Most engineers who have had to deal with reservoir supplies in areas of low annual rainfall (under 30 inches) have noticed, only too often, perhaps, the extremely local character of the showers and their frequent precipitation outside the limits of a catchment area where rain was badly needed. It is for this reason that in such areas it is particularly advisable to allow a cautious margin when estimating the run-off flow from a given catchment for a projected reservoir.

In " The Indian Borderland," 1880–1900, Col. Sir T. H. Holdich (1901, p. 14) tells the following story :

" At Kila Abdulla, where the Khojak pass drops on to the comparatively level plain of Pishen, and where the railway station of the same name now stands, we had an experience of what happens when a local flood washes down the Baluchistan hillsides after heavy rain. The length of the flood-basin leading up to the pass is inconsiderable, and the width of the water-way is in some places quite remarkable. It would indeed strike anyone unaccustomed to Baluchistan, as being wide absolutely out of all proportion to its length. But in Baluchistan the phenomenon of an irrisistable flood let suddenly loose and carrying all before it, after comparatively local rainfall, is not at all uncommon. It was such a flood that utterly destroyed the Bolan railway ere the Mashkaf alignment was adopted. When that railway was constructed the Baluch greyheads wagged their heads and said " Wait till a flood comes ; you haven't seen one yet." We waited a long time and then the flood did come, and it not only buried a large section of the line so deep that I doubt if the metals have even yet been recovered, but it washed away a *ziarat* (or shrine) or two belonging to these same Baluch advisers, a fact which seems to indicate that they had hardly appreciated the capacity of a Bolan flood themselves. On this particular occasion at Kila Abdulla the waters rushed with one rapid and comprehensive sweep straight down from the top of the Khojak (where we must presume that they originated) to the bottom, in the course of an hour. It was as if a reservoir had burst amongst the crests of the range and had emptied itself, as a bucket is emptied, on to the smooth unabsorbent slopes of the upper ridge, neither spreading wide nor losing force amongst the shaly gradients, but sliding in one unbroken mass of foaming, tearing, seething flood from the peaks to the plains. It was a flood of minutes rather than hours, and it took up the quarter-guard of the force in its embrace and whirled it away into the open almost before the half-drowned

sowars on guard could scramble up the low banks of the nullah."

EVAPORATION.—The percentage of the rainfall which is lost by evaporation is largely affected by climatic conditions. A water surface in an area subject to a hot climate, low average rainfall, long periods of sunny weather, and strong prevailing winds, is almost certain to suffer large losses by evaporation. The following figures were obtained from observations of the Ashti tank * near Sholapur in the Deccan, where the climate is very dry.

Months (1880–81)	Reduction of Surface level (feet)	Temperature (Fahr.)	Humidity (per cent.)	Wind (daily in miles)
December ..	0.12	71.4	46	140
January ..	0.40	70.7	41	169
February ..	0.65	75.6	34	170
March ..	0.65	82.2	27	154
April ..	0.95	88.6	28	154
May	1.02	90.4	30	250

In another case,† that of the Ambajhari reservoir near Nagpur, after deducting 200,000 cubic feet daily for the estimated draw-off, loss by leakage, etc., the residual loss due to evaporation was as follows :

	Evaporation inches per day	Temperature Fahr.	Humidity per cent.
10th October (1872) to 14th November	0.19	74.5	77
14th November to 24th December	0.15	70.9	80
24th December to 4th February (1873)	0.13	69.3	82
4th February to 16th March	0.14	77.2	63
16th March to 15th April	0.23	88.7	51
15th April to 7th May	0.37	91.7	38
7th May to 9th June ..	0.19	92.6	63

Roughly, 0.2 inches per day after adding 3 inches of rainfall.

In some parts of the cotton-growing areas of Western India, the evaporation loss is probably as high as 72 inches a year. What a loss of 6 feet means to the efficiency of a reservoir in such an area can be

* The tank has a water-spread of 1,412 acres. The monsoon arrives at the end of May. No water was drawn off for supply purposes. No rain fell during the period reviewed. No estimate is given for leakage.

† (See pp. 277–78, Blanford, quoted above.)

gauged from a simple calculation. (See adjoining Fig. 55.) In this case

L = length of water-spread;
B = length of dam at the water's edge, and
D = maximum depth of water in the reservoir.

Assuming the shape of the volume containing water to be as regular as depicted, the cubical contents of the reservoir is $L \times B \times D \div 6$. If the evaporation loss is one-tenth the depth, *i.e.* D/10 then the volume of water remaining in the reservoir will be $.9L \times .9B \times .9D \div 6$. This represents .729 of the original volume. The loss from the reservoir is therefore 27.1 per cent. If the evaporation losses lower the height of water in the reservoir by $\frac{1}{4}$D, then the volume of the remaining water will be $\frac{27}{64}$ths of the original volume. This would mean a loss of over 57 per cent. From these hypothetical calculations, it is at once evident that for such areas shallow reservoirs would be least

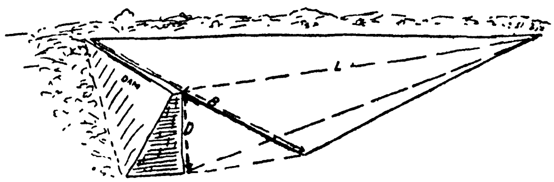


FIG. 55.
Reservoir diagram.

economical. To cope with a loss of 25 per cent. in an area subject to an annual evaporation loss of 6 feet, it would be necessary to build a dam to hold at least 60 feet of water (in a reservoir similar to that illustrated in Fig. 55).

To the geologist acquainted with the difficulties experienced by engineers in guarding against the silting up of reservoirs, the precautions taken in preventing the contamination of reservoir catchments, etc., it seems logical that expedients to reduce evaporation losses should also be tried. If shrubs and trees were planted on the borders of the water-spread, the force of the wind would be broken and the hottest air carried upward. This would appreciably reduce the evaporation. It is true that dead leaves would be objectionable in the reservoir, but this can be practically prevented by the use of a wire-net fence. Such a fence would also keep out animals which might otherwise contaminate the water.

E. H. L. Schwarz ("The Kalahari: or Thirstland Redemption," 1920, p. 15), speaking of the evaporating influence of winds, says that "unless the air is stirred by winds, the layer of saturated air just above the surface of the water protects the water, in that it itself cannot take up any further supply, and it yields what it holds slowly to the drier

air above. We have two striking instances: on the Gatun Lake (Panama Canal) in a hot, steamy atmosphere, because of the high and constant winds, the evaporation is 90 inches a year; at Kimberley (annual rainfall under 20 inches), where the air is so dry that readings of 25 per cent. moisture are obtained, because of lack of constant winds, the evaporation is only 60 inches. In Grahamstown (annual rainfall under 30 inches), with the high percentage of windy days, the readings run over 90 inches, about the same as at Johannesburg (annual rainfall under 30 inches)." He is "indebted to Mr. Ingham for the following figures for the evaporation at Johannesburg; the records are from the Union Observatory, situated in the centre of the suburbs, and the progressive decline of the yearly evaporation measures the effect of the increasing watering of gardens, cultivation, tree plantation, and so forth. On a small scale it accurately illustrates what will happen to South Africa as a whole when the Kalahari is irrigated, and forms a distributing centre for moisture.

Year	Evaporation loss (Inches)	Average 3 years.
1904	92.3	
1905	84.7	82.3
1906	70.1	
1907	76.7	
1908	66.6	70.9
1909	69.6	
1910	65.0	
1911	71.9	68.6
1912	68.9	
1913	69.7	
1914	61.0	62.1
1915	55.6	
1916	61.8	
1917	54.0	55.8
1918	51.6	

It is to be noted that evaporation outside Johannesburg, along the reef, remains about 90 inches.

PERCOLATION.—The percentage of the rainfall which sinks into the ground depends very largely on the nature of the surface upon which the rain falls. The greatest quantity will sink into a dry, cool, porous soil on level ground. None may be absorbed by a damp, bare, impervious surface on a steep slope. Between these extremes varying amounts will percolate into the ground. The percentages in the several cases will be influenced by the degree of porosity of the soil, the presence of vegetation, the declevity of the surface, the temperature and humidity of the air, and by the rate of precipitation of the rain.

Forests, wooded tracts, or grassy areas are, as a rule, not as good as open ground for the percolation of rain-water. Granitic rocks,

gneisses and schists, slates, shales and clayey strata are generally impervious unless deeply weathered or fissured. Basaltic lavas, such as those of Antrim (the Giant's Causeway) and other areas, although impervious in texture, are frequently traversed by numerous contraction joints. Hard quartzites and fine-grained sandstones are also impervious in texture unless heavily shattered. Soft or coarse-grained sandstones, gravels and boulder beds are excellent sources from which to obtain underground water if suitably located. In some tropical countries, the peculiar weathering product of rocks known as laterite occupies wide areas, usually as a capping to plateaux, and holds large volumes of subterranean water. Limestones are known the world over for the abundant supplies of *hard* water occasionally obtained from great caverns and fissures which occur in certain massive varieties of such rocks.

All the water that enters the ground by percolation tends to gravitate downward until it re-emerges at the surface as spring water, or passes into the stationary ground water which lies below the surface at varying depths. In most cases it is quite impossible to foretell, even approximately, what proportion of the rainfall will be lost by percolation. So much depends on the various considerations involved—the texture of the soil and underlying rocks, the surface vegetation, the rate and duration of the rain precipitation, etc. When a dam has been built, it may be possible to estimate the leakage by gauging the stream discharge below, but this does not help in elucidating the downward percolation to the underground water.

ABSORPTION.—It is the custom of American engineers to group together under the title absorption all those indeterminate losses to which the mean rainfall of a country is subject—*i.e.* by percolation, absorption by vegetation, and by rock weathering, etc. This grouping is largely followed in India, because it is one of convenience in the absence of experimental investigation. In fact Indian engineers go further and make allowance for evaporation and absorption as a single item.

The amount of water absorbed by growing plants or by the mineral components of rock during the process of weathering is seldom large. Under certain abnormal conditions, however, appreciable losses may occur. For example, certain clays which shrink enormously under the baking influence of the fierce heat of the sun absorb large volumes of water before they really become wet. The water thus absorbed is strongly held in the interstices of the clay and is only given up when exposed to further scorching in a hot sun for many days. This clayey ground cracks in great fissures 1 to 12 inches across and several feet deep where the clay is thick. Such water is consequently not available

for supply purposes. When wet, such clays form an excellent floor for a reservoir, but are liable to certain disadvantages. If stirred or disturbed by the movement of currents in the reservoir, this clay, which is exceedingly fine, renders the water muddy by becoming suspended in the water, and requires special treatment for is precipitation.

With a 30-inch rainfall, under temperate conditions, *e.g.* England, with its variety of surface relief and geological features, the distribution of the rainfall would be approximately:

	per cent	inches
Evaporation and absorption (by vegetation, etc.)	50	15
Surface run-off	25	7·5
Percolation	25	7·5

(See "Emergency Water Supplies," by A. Beeby Thompson, 1924, p. 11.)

YIELD OF CATCHMENTS.—The yield of a given catchment is obviously dependent on the run-off flow. This, as seen from the preceding pages, is subject to variation in accordance with the nature of the rocks exposed, the declivity of the ground surface, the area of the catchment, and the rate of precipitation and distribution of the rainfall. The nature of a catchment may be roughly classified as follows:

Excellent, one having very steep bare slopes of impervious rock;
Good, when the surface of the ground is steep and rock is exposed;
Fair, being midway between Good and Bad; and
Bad, with a flat surface of porous soil.

In his "Indian Storage Reservoirs," Strange gives the anticipated yield per square mile without considering the total area of the catchment. This method is perhaps justifiable in regions of low rainfall, as in a period of good rainfall the distribution of the precipitation is generally uniform; while in years of failure the showers are likely to be very local, and, in the case of small catchments, may possibly fall outside the catchment. The table given on the following page errs on the safe side, as it is calculated with minimum falls.

"If Strange's table shows that the anticipated yield is sufficient for needs the engineer can go forward with the scheme without hesitation; if the contrary is the case then the monsoon figures must be examined further as it is desirable to build a reservoir even though it is known that the supply from it is likely to fail occasionally. For example, it was found easy to secure 20 square miles of catchment for a gravitation project, but that it would not yield enough in a year when the monsoon rainfall was only 7 inches, in that year 40

Total rainfall inches	Anticipated yield (million cubic feet) per square mile of catchment area		
	Good (A)	Fair ($\frac{3}{4}$ A nearly)	Bad ($\frac{1}{2}$ A)
4	0.065	0.048	0.032
5	0.116	0.087	0.058
6	0.209	0.156	0.104
7	0.341	0.255	0.107
8	0.520	0.390	0.260
9	0.732	0.549	0.366
10	0.999	0.749	0.499
11	1.329	0.996	0.664
12	1.728	1.296	0.864
13	2.174	1.630	1.087
14	2.699	2.024	1.349
15	3.276	2.457	1.638
16	3.903	2.927	1.951
17	4.581	3.435	2.290
18	5.353	4.014	2.676
19	6.135	4.601	3.067
20	6.970	5.227	3.485

(See also G. T. Barlow's method, Hydro-Electric Survey of India, vol. III, Triennial Report, 1922, pp. 17-19.)

square miles was required; it was possible to secure 40 square miles but the scheme would then have been more costly and would have become a pumping scheme; the rainfall records for 45 years showed that a minimum of 7 inches had occurred twice and 9 inches (the next lowest record) was sufficient for a 20 square mile catchment, so the scheme was drawn up to suit the smaller area; the argument was that the expense and inconvenience of an occasional shortage would be more than counter-balanced by the saving afforded by the cheaper scheme, and further, though the rainfall in the 7 inches year might not yield enough, yet it was equally likely that a favourable distribution (heavy rain in one day) would save the situation." (See page 9, Section II, of proposed Handbook for Engineers, G.I.P.Ry., May, 1921.)

The above extract shows that there are times when an engineer must take chances. At the same time, in such cases, it is more than ever necessary for him to look carefully into the water-tightness of the reservoir site, and leave nothing to chance regarding the location of the dam which is to impound the water. These details are discussed in Chapters XI and XII of this book.

RAINFALL AND RUN-OFF DATA.—

1 inch of rainfall over 1 acre = 3,630 cubic feet of water;
= 22,687 gallons;
= roughly 100 tons.

1 inch of rainfall on 1 sq. mile (640 acres) = 2,323,200 cub. ft. water;
= 14,520,000 gallons;
= 60,000 tons of water.

A rainfall of 1 inch per month on 713 acres, or 7.13 inches per month on 100 acres, is equivalent to a flow of 1 cusec (1 cubic foot per second) per month. A cusec per 100 acres for a rainfall of 7.13 inches is said to have an irrigation duty of 100 acres.

An irrigation duty of

100 acres per cusec = 25,863 cub. feet per acre per month.
150 „ „ = 17,242 „ „ „
200 „ „ = 12,931 „ „ „
250 „ „ = 10,345 „ „ „ etc.

(See Mining Tables, Hatch and Vallentine, 1907, p. 75.)

The mean velocity throughout the cross-section of a channel is much less than the surface mid-stream velocity. In the worst cases—rough, shallow beds—it is about half. The least velocity is along the actual stream bed, more along the banks, and greatest in mid-stream.

Coefficients for ascertaining mean velocity from greatest surface velocity in channels are given by J. W. Mears (see *Triennial Report*, "Hydro-Electric Survey of India," Vol. III, 1922, p. 16).

Hydraulic mean depth feet	Very smooth channels	Smooth masonry	Rough channels rubble masonry	Very rough channels —earth	Channels and detritus
0.25	0.83	0.79	0.69	0.51	0.42
0.50	0.84	0.81	0.74	0.58	0.50
0.75	0.85	0.82	0.76	0.63	0.55
1			0.77	0.65	0.58
2		0.83	0.79	0.71	0.64
3			0.80	0.73	0.67
4			0.81	0.75	0.70
5				0.76	0.71
6		0.84		0.77	0.72
7				0.78	0.73
8					
9			0.82		0.74
10					
15					0.75
20					0.77

Col. Dicken's formula is very generally used in India for determining the discharge, D, of a river in cusecs. It is $D = C M^{\frac{3}{4}}$, where M is the catchment area in square miles and C a coefficient. This coefficient

varies greatly from 120 for large rivers of low gradient, like the Ganges, to 1,795 for other streams. 825 appears to be an average figure for an annual rainfall of from 25 to 50 inches. The question is, however, fully discussed by Buckley (see "Irrigation Pocket Book," 3rd Edn., p. 299 *et seq.*).

The discharge in cusecs of a clear overfall weir is found from the equation

$$Q = \frac{2}{3} c\, l\, h \sqrt{2\, g\, h}$$

where Q cusecs = discharge

c = coefficient, 0.577 for broad-crested weirs.
0.623 for narrow-crested weirs.
0.666 when length of weir is equal to width of tail channel.

l = length of weir in feet

h = depth of crest of weir below high flood level in reservoir, given in feet.

The discharge in cusecs of a submerged weir is to be found from the formula

$$Q = c\, l \sqrt{2\, g\, h_1}\left(h - \frac{h_1}{3}\right)$$

where Q, l, and h, are the same as above, and the coefficient c = 0.60 for cases where $h+h_1$ does not exceed 3 feet; for 4 and up to 12 feet increase c by 0.02 for every foot increase of $h+h_1$, above 3 feet. h_1 in feet = depth of level of water in tail channel below high flood revel in reservoir.

The above formulae do not apply in the case of a weir across a flowing river, as, in such a case, the velocity of the current above the weir has to be taken into account.

The Air.

Regnault's experiments showed that 100 cubic inches of dry air under a pressure of 30 inches of mercury and a temperature of 60 F. weigh 31.0353 grains, and that under the same pressure and temperature 100 cubic inches of water weigh about 25,252 grains. Thus air is nearly 814 times lighter than water.

1 cubic foot of air at 62° F. weighs .076 lbs. (=1.217 ozs. or 532.7 grains); at 32° F., .08 lbs. 1 litre at 32° F. weighs 1293 grammes. 13.141 cubic feet at 62° F. weigh 1 lb.

Normal atmospheric pressure 14.7 lbs. per sq. inch=2116.4 lbs. per sq. foot. A column of mercury 30 inches high or a column of water 33.947 ft. is supported.

Sir A. Abel and Sir A. Noble obtained (in researches with explosives) pressures in closed steel cylinders up to 95 tons to the square inch.

Air expands, or contracts, .002 of its volume per° F.

Air, under normal pressure, liquefies at −191° C. At 39 atmospheres pressure it will liquefy at −140° C.

Liquid air occupies $\frac{1}{800}$th the volume of air.

Wind Pressure and Air Resistance.

Formula, $P = .003\ v^2$.

Miles per hour		Feet per second		Lbs. per square foot
1	..	1.47	..	.003
2	..	2.93	..	.012
3	..	4.41	..	.027
4	..	5.87	..	.048
5	..	7.33	..	0.75
6	..	8.87	..	.108
7	..	10.29	..	.147
8	..	11.76	..	.192
9	..	13.23	..	.243
10	..	14.66	..	.300
11	..	16.12	..	.363
12	..	17.59	..	.432
13	..	19.06	..	.507
14	..	20.53	..	.588
15	..	22.00	..	.675
16	..	23.47	..	.768
17	..	24.94	..	.867
18	..	26.41	..	.972
19	..	27.88	..	1.083
20	..	29.35	..	1.200
25	..	36.70	..	1.875
30	..	43.98	..	2.700
35	..	51.32	..	3.675
40	..	58.68	..	4.800
45	..	66.01	..	6.075
50	..	73.34	..	7.500
55	..	80.67	..	0.075
60	..	87.96	..	10.800
65	..	95.29	..	12.675
70	..	102.62	..	14.700
75	..	109.95	..	16.875
80	..	117.28	..	19.200
85	..	124.61	..	21.675
90	..	131.94	..	24.300
95	..	139.27	..	27.075
100	..	146.60	..	30.000

Windmills.

To find the horse power

$$H.P. = \frac{A \times V^2}{1{,}100{,}000}$$

A = area of sails in sq. ft.

V + velocity of wind in feet per second.

Beaufort's Scale of Wind Force.

0	Calm	0—5 miles per hour.
1	Light air	6—10 " "
2	Light breeze	11—15 " "
3	Gentle breeze	16—20 " "
4	Moderate breeze	21—25 " "
5	Fresh breeze	26—30 " "
6	Strong breeze	31—36 " "
7	Moderate gale	37—44 " "
8	Fresh gale	45—52 " "
9	Strong gale	53—60 " "
10	Whole gale	61—69 " "
11	Storm	70—80 " "
12	Hurricane	over 80 " "

Weight and Measure of Water

Weight.	lbs.
A cubic foot of rain water (at 60° F.)	62.321
A cubic inch of rain water (252.5 grains)	.03617
A cylindrical foot of rain water	49.10
A cylindrical inch of rain water	.0284
A column of water 12 inch long, 1 inch square ..	.434
A column of water 12 inches long, 1 inch diameter ..	.341
A cubic foot of sea water	64.0
A cubic inch of sea water	.03703
1 imperial gallon of water	10
11.2 imperial gallons of water	112
224 imperial gallons of water	2240 (1 ton)
1.792 cubic feet of water	112
2.282 cylindrical feet of water	112
35.84 cubic feet of water	2240
45.64 cylindrical feet of water	2240

A cubic *centimetre* of water weighs nearly 17 minims (16.896); or 15.4 grains, or 1 *gramme*.

Measure.	Gallons.
A cylinder 1 foot long and 1 foot diameter	4.895
A cylinder 1 foot long and 1 inch diameter	.034
A cylinder 1 inch long and 1 inch diameter	.00283
A cubic foot	6.232
A cubic inch	.00360
A sphere 12 inches diameter	3.263
A sphere 1 inch diameter	.001888
277.274 cubic inches or .16 cubic foot	1
353 cylindrical inches	1

Cubic feet multiplied by 6.232 = gallons.
Gallons multiplied by .16046 = cubic feet.

THERMOMETER

C.	F.	
3500	6330	Temp. of electric arc.
"	"	Carbon vaporizes.
3000	5400	Temp. attained by thermit.
2800	5072	Oxy-hydrogen flame.
2500	4532	Osmium melts.
2225	4037	Iridium melts.
2231	4000	Heat in Bessemer furnace.
1710	3080	Platinum melts.
1530	2731	Wrought iron melts.
1400	2552	White heat.
1371	2500	Steel melts.
1200	2192	Orange-red heat.
1100	2012	Copper melts.
1063	1981	Pure gold melts.
1050	1922	Cast iron (lowest) melts.
970	1778	Silver melts.
700	1292	Dull red heat.
625	1157	Aluminium melts.
405	762	(about) Coal ignites.
400	752	Red-hot iron visible in dark.
357	674	Mercury boils.
316	600	Lead melts.
288	550	Gunpowder ignites.
215	420	Tin melts.
109	228	Sulphur melts.
100	212	Water boils.
79	174	Alcohol boils.
65	149	Fusible alloy melts.
61	142	Beeswax melts
60	140	Phosphorus ignites
50	122	
46	114	Paraffin melts.
44	111	Phosphorus melts.
40	104	
37·7	100	
36.8	98½	Human body in health.
35	95	
30	86	
25	77	
20	68	
17	62	Mean temp. of sea.
15	59	
10	50	Meam temp. of air (London).
5	41	
0	32	Water freezes.
−10	14	
−17·7	0	Mixture salt and ice.
−20	−4	
−38.8	−34·3	Mercury freezes.
−40	−40	
−55	−68	*Greatest natural cold on earth (antarctic).
−80	−111	Sounding balloon (9 miles high).
−100	−148	
−191	−312	Air liquefies under normal pressure.
−252	−422	Hydrogen liquefies.
−257	−432	Hydrogen freezes.
−268	−450	Helium liquefies.
−270	−454	Greatest artificial cold.
−273	−459	Absolute zero.

* Capt. Amundsen reported (in 1905) a temperature of −61.7° C. (or −79° F.) in Boothia (N. Canada). − 68° C. is said to have been experienced in Siberia.

Fahrenheit derived his scale from putting zero as the greatest cold then ascertained (by mixing salt and ice). The temperature of the human body was the other standard, and the space between these points was divided first duodecimally into 12° and later into one quarter of this, or 96°. It is also said that he divided this space into 100°, being in either case a couple of degrees out as regards blood heat.

Reaumur's scale (used in Germany) divides the space betwen the freezing and boiling points of water into 80°. To convert these scales—

$$F^\circ = \frac{9}{5} C^\circ + 32 = \frac{9}{4} R^\circ + 32$$

$$C^\circ = \frac{5\,(F-32)}{9}$$

$$R^\circ = \frac{4\,(F-32)}{9}$$

CHAPTER XIV

GEOGRAPHICAL CONSIDERATIONS

OROGRAPHIC MOUNTAIN RANGES.—Both the geographer and the geologist acknowledge two very distinct types of mountain ranges. In one type it is seen that the strata have been upheaved and bent and folded in such a manner that the axes of the folds run parallel to the trend of the mountain range. These mountain ranges are said to have Orographic Axes. The regions of most recent folding (geologically) are: (1) the American and Asiatic margins of the Pacific Ocean; and (2) the Mediterranean Zone, in which is included the Atlas range, the Alps, the Caucausus, the Himalaya, and the mountains of Burma. The latter zone joins the Pacific "girdle" in the vicinity of the East Indies. At an earlier period of the earth's history there were other directions of crustal folding. These are now recognised as the worn-down stumps of ancient orographic mountain chains, *e.g.* the Aravalli range of Rajputana in India, etc. Figs. 56 and 57 give cross-sections of the kind of structure to be expected in orographic mountain chains. The reader should consult "The Deformation of the Earth's Crust," by W. H. Bucher, 1933, a book full of useful facts in regard to special aspects of orogenic action.

RELICT MOUNTAINS AND PLATEAUX.—The second type of mountain chain is essentially due to erosion, and is called the Relict type of mountain. The strata affected may consist of horizontal beds or irregular masses. To this type belong the Highlands of Central India and the great scarp of the Western Ghats. In the latter case, the Western Ghats, the scarp is the steep seaward step of a large plateau, the Deccan, which slopes gently eastward. Practically all the big rivers of South India have their sources almost at the crest of the Western Ghats in sight of the Arabian Sea, although they flow across the whole breadth of the country and discharge their waters into the Bay of Bengal. Isolated plateaux, such as Table Mountain in Cape Colony, or the laterite-capped highlands in India and elsewhere, are further examples of Relict Mountains in which the rocks consist of horizontally-bedded material—sandstone in the one case, and basaltic lavas, as a rule, in the other. However, there are numerous cases where Relict Mountains locally simulate true mountain chains in

appearance, size and topography—everything, in fact, except orographic structure. The position is best summed up by saying that Relict Mountains are due to sub-aerial erosion, while Orographic Ranges are due to uplift by the forces of compression to which the earth's crust is subject.

HILLS OF VOLCANIC ORIGIN.—When a volcano is in eruption, there is little doubt as to its identity ; in other cases, the structure of a mountain must be investigated before it can be definitely described

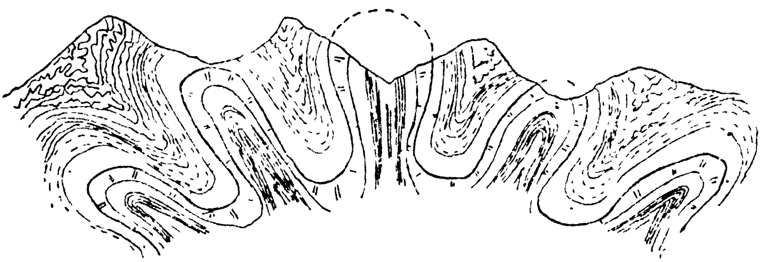


FIG. 56.
An ideal anticlinorium.

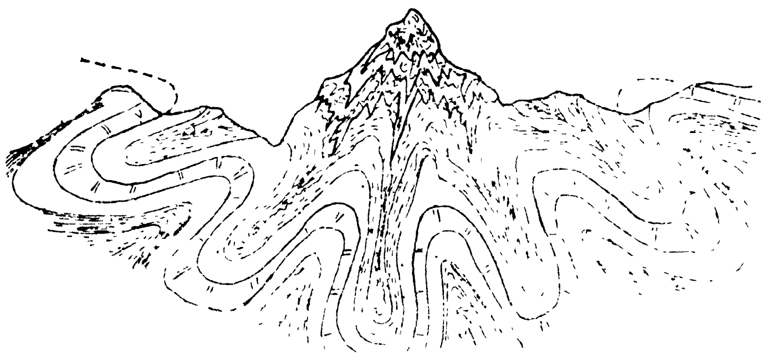


FIG. 57.
A typical synclinorium.

as of volcanic origin. It is true that volcanoes, by ejecting lava, ashes, and scoriæ, build up great conical masses round their craters, and that a chain of such cones may constitute a true range of volcanic hills ; yet it is to be remembered that a much greater volume of volcanic material, especially lava, has been erupted through fissures, and that the solidified material takes the form of level country which, by the erosion of streams, is frequently worn into deep ravines and isolated plateaux, which in time produce typical mountains. The terraced slopes of such basaltic ranges, and their flat-topped peaks, however, show that they are of the Relict type, although their constitution might lead them to be classed as volcanic hills of the flat-bedded lava variety.

EFFECT OF HIGH LANDS ON MOISTURE-LADEN WINDS.—In Chapter XIII, page 263, the subject of condensation and precipitation of moisture as rain was discussed in some detail. It was shown that, due to the presence of an intervening mountain range, which removed the moisture from a moisture-laden wind, the rainfall in the country to leeward might be so reduced as to finally result in such a tract becoming a desert. Baluchistan was given as an instance. The Himalayan Range is another example of the same phenomenon. In this case the moisture-laden south-west winds are not only robbed of their moisture, but compelled to ascend to great heights as they cross the Snowy Range. It is not to be forgotten that after these winds have precipitated the larger part of their moisture as rain on the southern slopes and as snow on the higher peaks and passes, they must descend very considerably on entering Tibet. In so doing their temperature is increased, as in the case of the Chinook winds, and their tendency is therefore to take up moisture instead of precipitating it. This they do from the shallow lakes of the Tibetan plateau. To this cause is ascribed the desiccation of the region north of the Himalaya. Similar phenomena are observable in most countries of great extent. A very striking example is afforded in the Bombay Presidency along the Western Ghats; the rainfall along the Konkan at the foot of the scarp is roughly 200 inches a year; along the crest of the scarp it varies from 250 to 400 inches; 12 miles to leeward of the scarp it averages less than 80 inches; and in another 20 miles eastward the annual rainfall is less than 20 inches and precarious at that.

GLACIERS.—Glaciers consist of sheets or streams of ice, with at times appreciable quantities of rock debris. They are ever moving slowly down from ice-clad regions to lower levels. Their weight and movement have an enormous scouring or gouging effect on the rock floor over which they move. As they proceed downward to the valleys, they melt slowly until a place is reached where the melting is as rapid as the forward movement. Here the glacier terminates and the glacial streams continue. In some instances glaciers flow directly into the sea, and, breaking off in great blocks, float away as icebergs.

The movements of glaciers form an interesting subject for study. Although moving very slowly—a few feet or yards a year during the summer months—there is considerable relative movement in the glacial mass itself, even in a given cross-section. It has been ascertained that the bottom of the glacier, although subject to melting as a result of the pressure of movement and weight, moves most slowly. The sides travel a little more rapidly than the bottom, but slower than the middle of the glacier. It is therefore not surprising that longitudinal cracks, or crevasses, appear in the glacier where the

valley floor is comparatively uniform in slope. The presence of a rock fall in the valley floor will of course make itself felt in the surface of the glacier by the development of cross-cracks and *seracs*. Although the movement of a glacier, as a whole, is comparatively steady in its lower courses, there is a good deal of sudden slipping forward at its source, especially where the mountain slope, on which the snow collects, joins the glacier. At this point, which is called the *névé*, the great active crevasses, known as the *bergschrund*, are to be found. Glaciers are important to engineers from two points of view. The study of glacial movement, especially at the *névé*, throws considerable light on the problem of landslides of loose homogeneous ground—the type so common on certain hill-slopes. The other aspect is that of irrigation water from glacial-fed rivers. Such rivers are very low in the winter months, when there is little thaw on the mountains, but

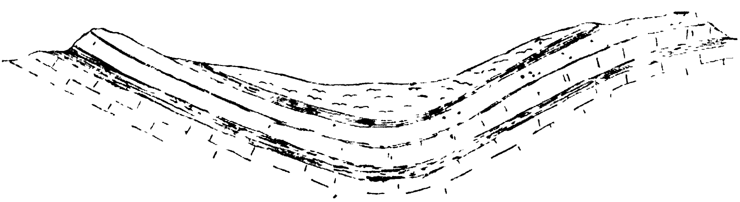


FIG 58
A synclinal (structural) valley.

during the hot or summer months a glacial-fed river flows very full; at such times water is usually urgently needed for irrigation purposes on the plains. No impounding of the river may be necessary, as the irrigation canal can tap the river by suitable headworks. Most of the great rivers of Northern India are fed from snowfields and glaciers during the hot months, and in almost every case—the Indus, Beas, Sutlej, Jumna, Ganges, etc.—they feed important canals on the plains, and till recently there was no need for the building of dams for storage purposes. On the peninsula of India, in the Deccan specially, where the rivers depend on the rains of the wet monsoon, it is a *sine qua non* that elaborate storage is generally necessary to maintain the irrigation canal supply during the hot months.

STRUCTURAL VALLEYS.—There are, as in the case of mountain ranges, two types of valleys from a geologist's point of view. These are known, respectively, as Structural Valleys and Erosion Valleys. The ideal type of Structural Valley is one which lies in a trough of bent strata, *i.e.* the valley is coincident with the axis of synclinal fold (see cross-section shown in Fig. 58). The Thames valley—particularly the lower reaches of the river from near Windsor, through London, to the sea—lies in a shallow trough or synclinal of

strata. However, this type of valley is exceedingly rare, and is seldom met with by the engineer in his field operations.

Another class of structural valley, and of more frequent occurrence, is that which follows the line of a fault or rift in the strata. The Great Rift Valley of Africa and the Jordan valley in Palestine are examples of this type (see Fig. 59). In the latter case a great fault, which lets down the strata to the east, traverses Palestine from north of the Lake of Galilee, through the Dead Sea, to the Gulf of Akaba. In countries where thick beds of hard and soft rock alternate and occur in an inclined position, it is not uncommon to find that the valleys and intervening ridges trend in the same direction as the strike of the strata. If the beds dip at comparatively gentle angles, 10° to 20°, the slopes on the sides of the ridges usually differ greatly; there is a steep face on one side, followed by a gentle or dip slope on the other. The same is

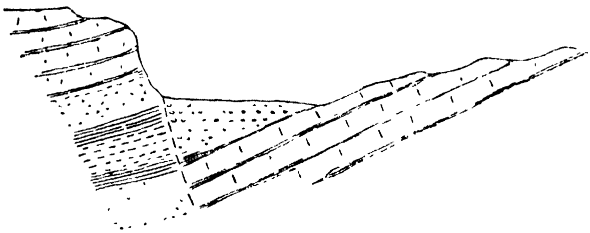


FIG. 59.
A fault (structural) valley.

naturally true of the valleys. Such features are often of importance to the engineer with regard to bridges, dams, and road alignments. They may have a military importance, as noted below:

"The heights of Dargai, now so famous as the scene of the engagement of October 20th, 1897, furnish a good example of the feature so characteristic of all the mountain ranges between Shinawari and the Safed Koh, the beds presenting a steep scarp to the south but falling away in a comparatively gentle slope—a feature which during the Tirah campaign was of great strategic advantage to the enemy, while equally disadvantageous to the British force attacking the position from the south." (See Hayden's 'Geology of Tirah and Bazar Valley,' North West Frontier Province of India, in *Memoirs Geol. Surv. India*, Vol. XXVIII, Pt. I, 1898).

Sometimes valleys occur in depressions which are caused by a synclinal fold, or trough, of the bedded rocks crossing the direction of drainage at right angles. In such cases the corresponding limbs of the fold may be seen, in section, as anticlinal or arched folds of the strata, on the sides of the valley both above it and lower down-stream. Possibly the stream will have cut a gorge through this lower arch, or anticlinal fold, of the strata. Occasionally a cross fault, which lets

down the strata on the up-stream side, will cause a fine valley with an out-fall through a gorge.

If the hill-sides are not too thickly wooded, there should be little difficulty in observing the dip of the strata in the *unfaulted* types of structural valleys. An examination of the exposed beds should also reveal the presence of porous strata and the possibility of their presence in the valley floor.

If the axis of a trough, or synclinal fold, is not horizontal, but tilted downwards, or pitches towards the up-stream side of the valley, it may be structurally to the advantage of a reservoir site. On the other hand, serious leakages may take place if the axis of the trough, or synclinal fold, is tilted down-stream at a greater angle than the gradient

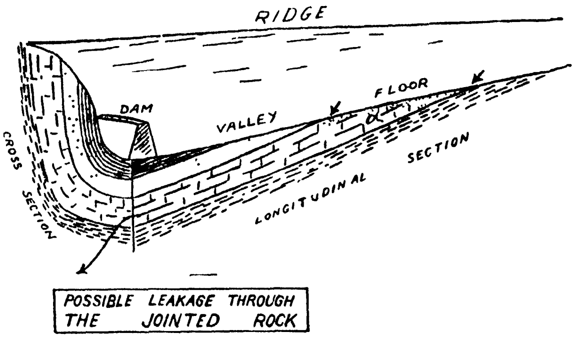


FIG. 60.
A pitching synclinal.

of the valley floor (see Fig. 60, which shows this case both in cross and longitudinal section).

In structural valleys of the faulted type with the fault parallel to the valley, there is usually a considerable leakage from the stream to the plane of the fault. The detection of a fault of this type should not be difficult, if the succession of beds in the areas on each side of the valley is carefully compared. The slopes on each side of a valley are seldom the same—those on the downward side of the fault, if dips are towards the valley, are usually less steep. This difference of slope on each side of a valley is often the result of tilted, conformable strata, the beds of which strike parallel to the valley, so that proof of a fault should be established and not presumed.

A cross-fault—one at right angles to the valley—may be an advantage. This is generally the case if the strata dip up-stream and abut, on the down-stream side, against impervious beds. Cross-faulting with the down-throw on the down-stream side generally results in waterfalls in the stream. Some of the cataracts on the Nile are said to have this structure.

The question of finally deciding in favour of, or against, a proposed reservoir site in any of the various kinds of structural valleys above described, will usually depend on the suitability of the location on which the dam is to be built.

EROSION VALLEYS.—Erosion Valleys are the commonest type with which the engineer will have to deal. The Grand Canyon of Colorado is perhaps the most typical example of an erosion valley. It has been carved out of soft, almost flat-bedded rocks by the sheer erosive power of the river. Less striking examples occur in many countries. In Western India, particularly in the vicinity of Mahableshwar in the Bombay Presidency, there are erosion valleys over 2,000 feet deep which have been carved out of bedded, horizontal sheets of hard basalt. Erosion valleys are not always associated with a simple geological structure. In mountainous country, where the ranges

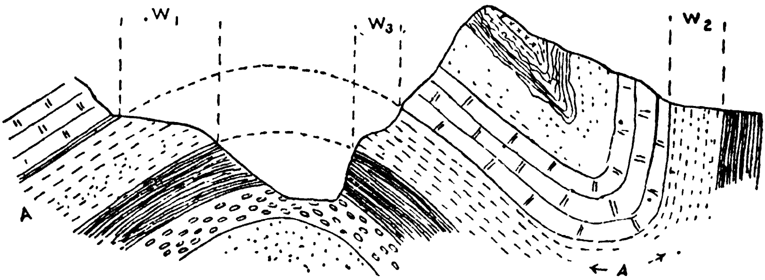


FIG. 61.
Normal mountain valley section.

represent true orographic features, the valleys are frequently found to lie in carved-out, anticlinal folds (see Fig. 61), while the ridges generally overlie synclinal folds (as shown in the same section of Fig. 61). The explanation of this is simple. The outer portion of an arched fold normally breaks under the tension of the bending; thus the strata on the arch will be more liable to erosion than the normal rock. On the other hand, the rocks in the inner portion of a trough fold will be tightly compressed by the bending, and the strata in the trough will, therefore, be less easily eroded. In some cases, more complicated structures are met with (see Figs. 58 and 59, in which corrugated strata are shown bent into an anticlinorium and a synclinorium, respectively).

Reservoir sites in any type of valley require careful examination. In the case of erosion valleys in folded rocks, the examination has to be minute. Porous strata may occur in the banks, or floor, of the reservoir. Rocks, which are normally impervious, may have become porous owing to their fractured condition.

VALLEY SECTIONS AND BEDS.—Although many geological writers speak of the V section of a river valley and the U section of

a glacial valley, their remarks invariably refer to mountain regions. In hilly country, the commonest section met with is some form of rectangle—either narrow across with high, walled sides, or wide with low, steep banks. In open country, or on alluvial plains, the cross-sections are very irregular. Most frequently the river is relatively wide compared with the depth of water. In some cases part of the bed has a deep channel, particularly at bends; otherwise it is with shelving shores on one side or on both. Except in the case of a river actively eroding its bed, it is unusual to find rock exposed in low-gradient streams in hilly or plain country; whatever rock is seen, invariably occurs in the banks between low water and flood level. In this zone the rock is usually fresh and undecomposed. Above flood level it is more common to encounter weathered rock.

Wide stretches of alluvial matter usually occupy the beds of streams in the plains. These deposits may frequently conceal a deep rock channel, which the stream has cut previously but which it has now covered with silt. Irrigation engineers, who have explored river sections by means of pits, or bore-holes, will probably recall instances when, because of a deep, concealed, rock channel, the projected establishment of a dam has had to be rejected, owing to the foundations being too costly for the area to be brought under command. Sometimes a narrow gorge is found to be deeply silted, the rock-bed being as much as 80, or even up to 100 feet below the bed of the stream. Examples of this type are to be found in almost all rivers flowing through rocky country—and particularly where gorges have existed, or where the strata strike parallel with the stream and comprise beds of differing hardness, etc.

MOUNTAIN STREAMS.—Perhaps the chief characteristics of mountain streams are the steepness of their gradients, their torrential character after rain, and their activity in eroding their beds. From an engineer's point of view, the following extract taken from one of Mr. R. D. Oldham's reports (*Memoirs Geol. Surv. India*, Vol. I, Part I, p. 174) is of great interest. He says, speaking of the Assam hill region:

"It will not be easy for those who have been accustomed to investigate countries where the average annual rainfall amounts to thirty or forty inches, distributed with tolerable equality over the whole twelve months, to form a fair estimate of the immense forces brought into play in these hills, where the fall of rain in 24 hours is not infrequently two feet six inches, or equal to the whole years fall in most places in Europe, and where the annual fall, not distributed over twelve months but concentrated into four or five, amounts to some fifty feet, or 600 inches."

Mr. R. D. Oldham "took an opportunity of visiting one of the

streams in these hills after a heavy and sudden fall of rain. The water had then risen only about thirteen feet above the level at which it had stood a few days previously; the rush was tremendous—huge blocks of rock measuring some feet across, were rolled along with an awful crashing, almost as easily as pebbles in an ordinary stream. In one night a block of granite, which I calculated to weigh upwards of 350 tons, was moved for more than 100 yards; while the current was actually turbid with pebbles of some inches in size, suspended almost like mud in the rushing stream . . . this water exerts its degrading force not only on the surface of the flats, or where, in rushing over the precipitous scarps, it excavates deep basins beneath, but it pours through the many fissures and clefts in the sandstone and limestone, and springs from the solid face of the rocks at different levels, tearing with it fragments of the hardest masses, and precipitating them into the gorges below.

"The rapid degradation . . . is well shown by the vast amount of suspended matter, which is carried down by the streams issuing from the hills during the rains. I had more than once seen streams, which in the drier weather were beautifully pellucid, so turbid and charged with suspended matter, that a white card was invisible at a depth of one inch and a half! that is, through a stratum of water of that thickness. I also measured the bulk of such sediment in a carefully divided tube, and found it more than once to amount to one-fifth of the total bulk, and in one case to nearly one-third. In all these cases this sediment was a fine clayey sand."

After reading such a description, perhaps it may be remembered that:

"the transporting ability of a current of water varies with the sixth power of its velocity." (J. F. Kemp.)

If we have current of such a velocity that it is capable of moving one-inch cubes of rock of, say, a density equal to quartz (2.65), and by means of heavy rain the velocity of this stream is doubled, the flood water will be capable of moving four-inch cubes of the same material, *i.e.* masses equal to 64 times the bulk of the masses which were moved by the original stream. An appreciation of this law helps us to understand how it is that in times of flood a stream may be capable of rolling forward boulders of great size.

In the Himalayas the erosion due to the mountain streams has been so great that the valleys are deep and steep-sided and their slopes subject to considerable landslips. Most of the bridges which are made take the form of suspension or cantilever types—chiefly the former. This is necessary, because the height of the piers would be out of all proportion to the length of the bridge; besides, the securing of their foundations, either in the narrow stream-bed or on the precipitous slopes, would be too expensive. Photograph 7 shows a typical valley with a suspension bridge in the Central Himalaya.

RIVERS.—The term river is normally applied to a large stream

flowing in a valley with a comparatively low gradient. When the gradient is uniform, the stream will be actively engaged in excavating its bed and scouring its concave banks. If the gradient is suddenly lessened and the velocity of the stream reduced, there is usually a deposition of silt, or gravel, depending on the size of the material carried by the stream and the actual velocity of its current. With regard to this aspect of a stream, J. F. Kemp (see "Handbook of Rocks," 5th Edn., 1911, p. 94) says:

"All streams or currents charged with suspended materials exercise a sorting action during the deposition of their loads. With materials of the same density the sorting will grade the deposit according to the size of the particles. With materials of different densities, smaller particles of heavier substances will be mixed with larger particles of lighter ones. Assuming a swift current, we readily see that, when it slows up, the large and heavy fragments drop first of all; then the smaller fragments of the heavier material and the larger ones of those successively lighter; until at last the smallest particles of the lightest alone remain in suspension."

From experiments made by Bossut, Dubuat, and others, the size of particles conveyed by rivers flowing at different velocities is as follows:

Vel. per sec.	Materials conveyed by stream
3 inches	Fine potter's clay.
6 "	Fine sand.
8 "	Coarse sand—size of linseed.
12 "	Fine gravel.
24 "	Pebbles—one inch diameter.
36 "	Angular stones—size of an egg.

(See "The Supply of Water to Towns," Pt. I, 1865, p. 24, by Baldwin Latham.)

In this connection the following supplementary data are also useful:

SCOURING VELOCITIES.

Material	Feet per sec	Miles per hour
Soft clay	0.25	0.17
Fine sand	0.50	0.34
Coarse sand and gravel as large as peas ..	0.70	0.48
Gravel as large as French beans	1.00	0.68
Gravel 1 inch diameter	2.25	1.54
Pebbles 1½ inches diameter	3.33	2.27
Heavy shingle	4.00	2.73
Soft rock, brick earthenware	4.50	3.08
Rock, various kinds	6.00	upwards

(See Marine Works, by E. Latham, 1922, p. 137, after Rankine, "Civil Engineering.")

"Experiments in the Missouri River have proved that a considerable current of water will pass around a fixed curve of 300 feet radius without causing eddies, and that an angle of 30 to the current is approximately the one at which a silt bank can approach a fixed point without much erosion." (The Improvement of Rivers by B. F. Thomas and D. A. Watt, 1905, p. 74 L.)

With regard to the flow of water in open channels and the velocity of the current in different parts of the cross-section, Trautwine, 1907, p. 560, considers the maximum velocity is found about halfway between the banks and about one-third the depth below the surface. The bottom velocity is roughly five-eighths the mean velocity. The mean velocity can be taken as four-fifths the maximum surface velocity.

The scouring action of a stream is said to be very nearly proportional to the square of its velocity. However, this is complicated by various factors—the relative roughness and uniformity of the channel, the nature of the rock in the bed, and the amount of suspended matter in suspension in the current. If obstructions are placed in a stream, such as the piers of a bridge, a slight impounding of the water will occur as a result of which "head" there will be an increased velocity under or around the obstruction. This may lead to scouring if the velocity is sufficient to scour the material of the obstruction or the stream-bed. (See Trautwine Tables on p. 577, 1907 Edn.)

Whereas small mountain streams tend to follow straight courses down steep slopes, the larger mountain streams may be deviated by various causes. Their channels are chiefly influenced by the nature of the rocks they traverse. They may follow a bed of soft rock for miles until deflected by the sudden appearance of a hard band. A landslip, by choking the valley and impounding the water of the stream, may lead to the lake thus formed overflowing at a saddle, or result in the out-flowing stream following a fresh course in a new direction. In the case of rivers flowing over rock beds in open or less hilly country, the nature of the rocks and their geological structure continue to be the factors determining the courses which such bodies of water will follow. At the same time it must not be forgotten that all such streams are ceaselessly at work lowering their gradients, by eroding their beds, cutting back into the hills, and extending their courses. In some places they may be depositing their suspended load of silt and gravel; in other places they may be re-excavating beds of debris which they had previously deposited; but they are continuously engaged in attaining a gentle gradient.

It is not until a stream, or river, has emerged into flat ground, composed of very soft rock or alluvial material, that they develop the habit of wandering laterally—meandering, as it is termed. On such ground, a small stream may twist in close curves and loops to an

amazing extent. As a rule, the larger the volume of water, the longer the lengths of these loops; but the gradient still plays an essential part in determining the size of these curves. It is obvious, however, that the nature of the material forming its banks will, by the resistance it offers to scour, also affect the tendency of a stream to wander.

The Nile at Aswan appears to have been diverted into its present channel by trough faulting, at a comparatively recent geological date. The old channel is still to be seen east of the Aswan dam. However,

"the theory of faulting, while explaining the migration of the river westward, does not itself account for more than a small proportion of the lowering of the river level. Such lowering (of the bed) is almost entirely due to erosion (corrasion!), though the cause of the erosion and its intensity were due to faults. The river has pursued substantially its present course for at least 10,000 years, and every moment, night and day, winter and summer, throughout this long period, the river has been grinding down its channel."

Even at the present day immense numbers of pot-holes are being eroded in the hardest rocks by eddying currents acting on sand and stones lodged in the hollows of the surface. Continually honey-combed by pot-holes, and penetrated by joints and crush-zones, the hardest masses of granite are being broken up and carried away by the annual rush of flood waters.

It may be mentioned that some ashlar blocks of granite were left for a few months (in 1902) in the bed of the Nile below the Aswan dam. These blocks were originally rough cubes with 60 cm. edges, but after the grinding they received in the issuing waters during the above short period, they were completely rounded into boulders.

The amount of erosion (vertically) of the hard gneiss in the Nile at Semna has been estimated to be 8 metres in 4,200 years. It appears that the Pharaohs of the twelfth dynasty caused a long series of high water marks to be graven on the rocks at Semna, and it is from these data that the above calculation has been made.

In a very valuable paper by Fergusson ("The Delta of the Ganges?" Q.J.G.S., Vol. XIX, 1863, p. 322) this subject is discussed as follows:

"A river is a body of water in unstable equilibrium, whose normal condition is that of motion down an inclined plane; and if we could abstract all the natural conditions of inequality of surface or soil, it would flow continuously in a straight line; but any obstruction or inequality whatever necessarily induces an oscillation, and the action being continuous, the effects are cumulative . . . and the oscillation goes on increasing till it reaches the mean between the force of gravity tending to draw it in a straight line and the force due to the obstruction tending to give it a direction at right angles to the former.

"If this be so—the extent or radius of the curves will be directly

proportional to the slope of the bed of the river. If, for instance, a river were flowing down a regular slope, through a perfectly homogeneous soil, with a fall of say, 10 feet per mile, or 1 in 500, the curves would be so extended as to appear nearly a straight line on the map. With a fall of 1 foot per mile, the radius of the curve is, as nearly as I can ascertain, double that of a river with a fall of 6 inches; and when the fall is about 3 inches per mile, the direct and tangential forces so nearly balance one another that the curves are practically semi-circles. In the latter case the chord of the curves is practically four times the width of the river. Thus a river 1000 feet wide would oscillate once in 4,000 feet in the general direction of its course, and the extent of the curve, measured along the centre of the stream, is a little more than 6,000 feet.

"Between a fall of 6 inches and 1 foot per mile, the oscillation is, apparently, once in about 6 times the width; above a foot it rises to one in ten or twelve, above which it is extremely difficult to find examples uninfluenced by natural obstructions. It need hardly be remarked that these observations apply to rivers when their beds are full, which is the only time when they are shaping their courses."

DELTAIC RIVERS.—In the deltaic portion of a river, the effects of scouring become less conspicuous and the problem of silting far more important. The suspended material is much finer in size than that which is met with higher up-stream. Flooded areas and marshes are of frequent occurrence.

"When the whole country is covered with water, moving rapidly towards the sea in the river channels, and stationary throughout the intervening marshes, the dead water of the marshes prevents the floods of the river from breaking out of the channels, and, by stopping the course of the silt-charged water along the edges of the creeks and streams, forces it to deposit the sediment it has in suspension. Hence gradually arises a system of river channels, traversing the country in many directions, between banks which are higher than the intervening flats, and these flats form persistent marshes." (R. D. Oldham, 2nd Edn. Manual Geology of India, p. 440.)

It is not uncommon to find one or more channels almost cut off from the discharge of the main river and in which the seaward velocity is very small. Such channels are subject to the inward flow of the flood tide and the outward sweep of the ebb tide. The rise of the tide often causes a flooding of adjacent low-lying ground, and the reduction in the velocity of the flow due to this cause, and at the turn of the tide, leads to a deposition of silt. Thus in process of time the low-lying grounds will silt up into marshy ground and, finally, the channel itself will be choked by the deposit of silt.

An excellent recent example of this is furnished by the Ganges delta of Bengal. The sewage of the city of Calcutta is discharged into the Bidyadari tidal channel which, at flood tide, used to overflow into the Salt Lakes; now this overflow has practically ceased, and the

Bidyadari channel is itself silting up. An attempt is about to be made to dredge out the Salt Lakes and part of the Bidyadari channel, so as to restore the original conditions, and, in addition, to pump the sewage into the channel, thus imparting to it a seaward velocity.

Further down the delta it is known that

"the suspended material becomes excessively fine, the ratio of its surface to its volume is so extremely high that adhesion, or chemical action akin to hydration, or some other influence not well understood, operates in pure, fresh waters, so as to render sedimentation practically impossible, even if the medium be perfectly quiet. W. M. Brewer has shown by a series of experiments with all sorts of clays, lasting over many years, that if we introduce into such an emulsion a mineral acid or a solution of salt or of some alkali, the turbidity clears with remarkable quickness. When, therefore, sediment-laden streams flow into the ocean, or into salt-lakes, even the finest part of their load speedily settles down." (Kemp, Handbook of Rocks, p. 94.)

This aspect of the case is well brought out by Wheeler ("The Sea Coast," 1902, p. 65), as shown in the accompanying table.

PRECIPITATION OF SILT IN FRESH AND SALT WATER.

	Number of grains per linear inch	Material	Time taken to settle		Water clear		Feet per min	
			Fresh	Salt	Fresh	Salt		
			m. sec	m. sec	h m.	h m		
1	5	Small pebbles ...	0 1	–	–	–	0.5	water not discoloured
	10	,,	0 1½	–	–	–	0.42	,,
	20	Coarse sand	0 2¼	–	–	–	0 21	,,
	20–60	,,	0 4	–	–	–	0.13	,,
2	100	Sand ...	0 10	–	–	–	5.04	,,
	200	,,	0 25	–	–	–	2.40	,,
3	300	Warp (silt) Trent	0 43	0 45	0 1	0 1	1.20	water scarcely discoloured.
4	500	Silt salt marsh ...	2 0	2 0	0 6	0 9	0.42	water turbid.
5	600	Alluvium River Parrett	4 0	2 40	0 15	0 18	0.22	,,
6	1000	Warp salt marsh ...	8 0	9 0	1 0	0 33	–	,,
7	1400	Fine warp (Dutch River)	12 0	15 0	3 30	22 0	0.70	,,
8	1440	Boulder clay ...	24 0	0 22	0 43	0 30	0.35	,,
9	1500	Tilbury basin ...	18 0	18 0	10 0	9 0	0.46	,,
10	1600	Brick clay	17 0	15 0	1 30	1 0	0.40	,,
11	2000	Alluvium Boston Dock ...	33 0	28 0	7 0	1 30	0.11	,,

(*See* Wheeler's "The Sea Coast," 1902, p 65.)

The samples were placed in glass test-tubes 1 foot long and of ½ inch diameter, filled with clean water up to the 10 inch mark.

From the above table it is seen that in some cases—No. 11, the alluvium from Boston Dock—the fine particles settle quicker in salt water than in fresh water; in other instances—No. 9, silt from Tilbury Basin—there is little difference in the rate of settling in fresh or salt water; while in a few cases—No. 7, the fine warp from a Dutch river—the sediment actually settles more rapidly in fresh water than in salt water.

It has been experimentally ascertained that the sediment of the Mississippi delta takes 10 to 14 days to settle in fresh water, whereas the same material is precipitated in from 14 to 18 hours in a salt solution or weak sulphuric acid (see "Report on the Mississippi River" by Humphreys and Abbot, 1861). It was from this report that the opinion became fixed that any suspended matter in river water settles rapidly when discharged into the sea, and this has been put forward as of prepondering influence in the formation of deltas. The subject of base exchange, however, requires examination in these cases—*i.e.* the calcium and magnesium in the silts would tend to be replaced by the sodium in water, and this effect may help rapid precipitation of the silt.

Some idea may be formed of the quantity of material brought down by a great river and carried to its delta from the following statement:

"The discharge of the Mississippi River is about 19,500,000,000,000 cub. ft. of water per year, and the sediment it carries in suspension is estimated to weigh about 812,500,000,000 pounds. This is equivalent to about 6,714,694,400 cubic feet. It is estimated that about 750,000,000 cubic feet of sediment is rolled along the bottom, giving a total of 7,468,694,400 cubic feet as the aggregate annual load carried to the Gulf by the river. This would be adequate to cover an area of one square mile to a depth of 268 feet per year." ("Geology: Processes and their Results." Chamberlin and Salisbury, Vol. I, 1904, p. 106).

The subject has been elaborately treated by Professor Vernon-Harcourt (see *Proc. Inst.C.E.*, Vol. CXLII, 1900, pp. 272–287). This writer draws attention to the various chemical and physical causes which interfere with the settling of silt in estuaries and in the sea. The attached tables (*a*), (*b*), (*c*) and (*d*) have been taken from the above paper.

"Lastly," Harcourt says, "it must be noted that very fine silt floating in the upper layers of the river water, does not really mix at once with the sea water . . . but is . . . partly borne along by the . . . fresh-water current, over the top of the denser sea water . . . the muddy out-flow from the Nile is very distinctly visible crossing the out-let of Port Said Harbour, at a distance of about 35 miles from the nearest mouth of the river . . . and if the action of sea water on river

silt was as rapid, a turbid river like the Hugli should become clear on entering the Bay of Bengal, whereas its waters are as densely charged with reddish brown silt beyond its outlet, as at Calcutta 100 miles up the river."

(*a*) SEDIMENTAION IN MINUTES PER FOOT.

Solution	Strength of Solution	Deltaic Silts			Component Substance		
		Hugli	Rhone	Danube	Lime-stone	Peat	China Clay
Sea salt, saturated sp. gr. 1.2 ..	—	7½	7	6⅔	13	—	24
Sea water sp. gr. 1.024 and 1.018 ..	1/30	23	24	26	12	35	93
Thames water ..	1/3500	27	25	34	18	25	71
Pond water ..	—	22	14	30	11	20	21
Distilled water ..	—	56	32	65	14	54	65
Sodium chloride sp. gr. 1.058 ..	1/10	23	29	28	17	21	151
Magnesium chloride sp. gr. 1.03 ..	1/10	28	34	31	30	22	135
Magnesium sulphate sp. gr. 1.04 ..	1/10	37	40	38	14	34	165
Calcium sulphate ..	1/420	23	22	26	9	24	125
Potassium chloride sp. gr. 1.052 ..	1/10	16	17	20	15	28	156
Potassium sulphate sp. gr. 1.05 ..	1/118	17	21	25	11	24	152
Calcium bi-carbonate	1/2700	26	27	31	12	35	84
Magnesium carbonate sp. gr. 1.018 ..	1/48	30	38	40	9	35	67
Sodium carbonate sp. gr. 1.032 ..	1/10	30	45	51	10		180

(*b*) ANALYSES OF RIVER SILT.

	Hugli	Rhone	Danube	Dnieper	Nile	Missi-sippi
Organic matter and combined water ..	3.21	1.73	3.58	1.24	5.91	4.16
Oxide of iron and alumina	13.78	6.92	10.08	3.02	21.25	9.55
Lime	3.64	19.24	4.56	1.41	2.40	1.16
Carbonic acid ..	4.41	14.91	5.66	1.90	7.78	2.69
Magnesia and alkalies	0.28	4.80	0.21	0.21		0.66
Silica and insoluble silicates	74.68	52.40	75.91	92.22	62.66	81.78
Total	100.00	100.00	100.00	100.00	100.00	100.00

(c) SALTS PER GALLON OF SEA WATER.*

Sodium chloride	1,851	grains
Magnesium chloride	221	,,
Magnesium sulphate	148	,,
Calcium sulphate	93	,,
Potassium chloride	52	,,
Calcium carbonate	3.3	,,

(d) The River Hugli, above Calcutta, contains in solution, per gallon of water, the following salts :

Calcium carbonate	7 to 11 grains.
Magnesium carbonate	4 ,,
Calcium sulphate	nil.
Sodium carbonate	up to 1.5 ,,
Organic matter	7 ,,
Sodium chloride	see below.

at Cossipur (100 miles up)	in March	6	grains.
	in May	32.5	,,
at Pulta (111 miles up)	in March	0.6	,,
	in May	3.6	,,
at Chinsurah (118 miles up)	in March	0.7	,,
	in May	1.6	,,

From Harcourt's and Wheeler's experiments, and a study of the phenomena connected with colloidal matter, it appears that the subject is not simple, but largely depends on the fineness of the silt, its chemical and physical characteristics, the composition of the water into which it is carried, the presence of currents, and the sign of the electric charges on the colloid particles with respect to the electrolyte into which the sediment is carried.

In the ceramic industry it is a well known fact that the addition of sodium carbonate, or caustic soda, helps to keep most clays in suspension in the liquid (water) : whereas the addition of sodium chloride, or an acid, coagulates the clay and causes rapid precipitation. These facts are utilised in a practical way in the manufacture of porcelain.

The electro-osmosis process for the purification of clay utilises the fact that most clays in suspension are negatively charged electrically, so that by passing an electric current through the clay slip, the particles of clay migrate to, and are deposited on, the kathode of the circuit.

It is also known that clays can be used for removing finely-divided, organic, oily matter from certain fluids. The organic matter of the fluid carries a positive electric charge, and can therefore be precipitated by colloid matter, such as clay, carrying a negative charge. Domestic sewage, on the other hand, carries a negative charge on its colloidal

* To convert grains per gallon into parts per million divide by 0.07 and vice versa ; to convert parts per million into grains per gallon multuply by 70

particles, and this material can therefore be precipitated by colloids, such as alum, which develop a positive charge on its particles.

It is here worth mentioning a curious feature of " base exchange." E. Mackenzie Taylor (see *Fuel*, Vol. V, No. 5, 1926, p. 196) says:

". . . so long as the sodium-adsorption complex is in the presence of an excess of the neutral sodium salt, the complex, in mass, remains permeable. When the excess of the neutral sodium salt is gradually removed the mass gradually becomes impermeable to both water and gases."

He says further:

" A quantity of soil was placed in a Buckner funnel and washed with a strong solution of sodium chloride. The solution of sodium chloride was then replaced by water and the amounts percolating in successive ten-minute intervals noted."

No. of ten-minute intervals.	Amount of water percolating.
1	153
2	27
3	13
4	7
5	4
6	2
7	1

It will be seen that, as the soduium chloride is removed from the soil, the rate of percolation rapidly decreases until it almost ceases.

CHAPTER XV

RIVER CAPTURE AND TIDES

MUD BANKS.—In South India, along the Travancore coast between Aleppi and Narakal, there are certain " back-waters " which, although exposed to the full force of the incoming seas, have smooth water even during the height of the south-west monsoon. These smooth water anchorages have in consequence attracted the attention of navigators since very early times. The calming of the waves is thought to be due to suspended mud in the water.

Investigation has shown that there are submerged mud banks, 11 miles long, parallel to the coast. These banks appear to represent the out-crop of a peculiar oily mud which underlies the sandy bed of the " back-water." It has been observed that the sea level in the back-waters is appreciably raised during the rains by the flood water discharges from the land. It is thought that this additional hydrostatic pressure on the bed of the back-waters, acting through the porous sand, is sufficient to cause an extrusion of liquid mud at the out-crop of the mud bed—*i.e.* under the sea, in the vicinity of the mud banks. An emission of liquid mud near the " banks " would tend to push them up in the path of the incoming seas. The effect would be that the waves would disturb the mud in the shallowing water and break along the crest of the " banks." In consequence of this, the seas would be smoothed off as they passed over the banks into the back-water. (See P. Lake ; *Rec. Geol. Surv. India*, Vol. XXIII, Part I, 1890, pp. 41–47 ; also R. D. Oldham, " Geology of India," 2nd Edn., pp. 405–406.)

Sir Charles Lyell (" Principles of Geology," Vol. I, pp. 447–454) has mentioned the sudden appearance of islands of a peculiar, stiff clay in the " passes " of the Mississippi delta. Some of them are said to stand 100 feet out of the water and to be associated with emissions of gas, chiefly carbon dioxide and marsh gas, and brine. He considered that these islands owe their origin to the squeeze caused by the load of river silt deposited in the vicinity. He likened the action to that of the pressure of an embankment built across boggy ground, whereby the fluid matter of the bog is caused to rise or bulge on either side of the embankment.

RIVER "CAPTURE."—Mention has already been made of the fact that all steep-graded streams tend to lengthen their courses, and in so doing frequently cut back across a mountain range. It is therefore not surprising to discover that in thus enlarging their catchment areas they occasionally absorb the drainage of other streams. Examples of this kind are to be found in most countries—sometimes within the limits of a small tract; at other times on a large scale. In the Himalayas, many of the large south-flowing rivers have cut through the main range and captured the drainage of streams in the Tibetan river system. It is suspected that the present Brahmaputra river of Assam originally had its source in the hinterlands of the Abor country, north of Sadya, in the Eastern Himalayas, and that in that remote period the Tsang Po of Tibet flowed eastward through Yunnan to the China Sea. In process of time, it is conjectured, the Brahmaputra cut off the Chinese section of the Tsang Po, and diverted the Tibetan river through the Himalayas to the plains of Bengal and the delta of the Ganges. Recent investigations by Dr. A. M. Heron go to show that the Arun river of Bengal and Nepal is now threatening the Tsang Po of Tibet with a second deflection southward to the Bay of Bengal.

An interesting paper on this subject of stream capture, under the title "The Future Beheading of the Son and Rer Rivers by the Hasdo," by Dr. L. L. Fermor, is given in the *Records Geol. Surv. India*, Vol. XLIV, Part 3, 1914.

Sir E. H. Pascoe, as well as Dr. G. E. Pilgrim quite separately, has recently brought forward much data to account for the origin, or, as he calls it, the birth of the present Ganges. He advances weighty reasons for believing that during the period in which the Siwalik strata of the Himalayan foot-hills were being deposited, a river, having its source at the head of the Brahmaputra valley of Assam, flowed westward along the Siwalik tract to the Punjab, and then turned southward to discharge its waters into the Arabian Sea. This supposed river, which he aptly calls the Indo-Brahm, was curtailed by the head-stream erosion of a steep-graded river flowing into the Bay of Bengal. The activity of this Bengal stream in lengthening its course and lessening its gradient has been responsible for the present river systems of the Brahmaputra to the east and north, and of the Ganges and Jumna Rivers on the west.

In his book, "The Kalahari: or Thirstland Redemption" (1920, p. 54), E. H. L. Schwarz has much to say on the shrinkage of certain lakes which occupied the depression of what is now the Kalahari desert. The computed areas of these lakes of the Kalahari may be compared in size with the present great lakes of Central Africa:

Lost Kalahari Lakes.	sq. miles.	Central African Lakes.	sq. miles.
Greater Ngami	30,000	Victoria Nyanza ..	26,828
Makarikari	15,000	Tanganyika	12,700
Etosha Pan, 20 feet deep..	5,000	Nyassa	11,600
Total area of the lost lakes	50,000	Total area	41,128

" It will be of interest here to trace the history of Lake Tanganyika, which has been worked out by J. E. S. Moore and M. Fergusson, because it shows the vicissitudes through which our inland lakes pass. In the beginning, Tanganyika drained into Lake Kion, and thence into the Albertine Nile, and eventually into Egypt. Within the historic period volcanoes were thrown up north of Kion, and the waters of Kion and Tanganyika were cut off from the Nile system ; from this time the Nile has been shrinking. From these considerations it would seem probable that after Kion had filled up through the formation of the Infumbiro volcanoes, its overplus of water flowed into Tanganiyka for a great number of years, until the level of this lake was raised. One of the head-streams of the Congo, then the Lukuga, worked by head-stream erosion across the watershed, and started draining the lake. It is a remarkable fact that the outlet of Kion, the Rusisi River, is five or six times the size of the Lukuga ; if the Rusisi River was to be cut off from Tanganyika, then the lake would fail to over-flow, and would become salt. The water of Tanganyika is even to-day somewhat salt. It seems to be fresher than when Livingstone and Stanley examined it, while, as both these explorers aver, there are traditions among the Arabs that, in the recollection of living men, it was a lake that had never flowed out at all.

" This view of the matter will at once explain the fact that Tanganyika has otherwise unaccountably fallen some forty feet, possibly a great many more feet, within no great number of years, the overplus of water in it having worn away a channel to the west to such an extent that it will never regain its ancient high level. In other words, the process of draining, which is now complete in the Ngami region, has started in Tanganyika, and is proceeding at a rapid rate. The waters of Nyassa have similarly decreased, but those of Albert Nyanza have increased."

It may be stated that in Livingstone's time, about 1845, there was a sheet of water 60 miles wide at the present site of the Ngami depression, and that in 1897 Passarge found a swamp in the same area. Schwarz is of the opinion that this lake has been drained by the Zambesi which has actively cut back its course since about 1820. This writer also points to the Niger and the Congo as having originally a northern outlet across the Sahara into the Mediterranean. These older rivers were captured by a steep-graded, energetic stream from the coast. The Niger catchment continues to be reduced by coast streams which are carving into the highlands and appropriating the drainage which flows northward. The Proto-Congo diversion is a little more proble-

matic. (See also an account of the origin of the Niger drainage in "Geology and Geography of Northern Nigeria," by J. D. Falconer, 1911, p. 243.)

RIVER FLOODS.—Almost every year a devastating flood in one or other of the large rivers of Asia, usually those of China or India, is brought to the notice of the reading public. The engineers of most countries, on the other hand, give earnest attention to the flood control of the rivers with which they have to deal. As a general rule these floods are due to excessive precipitation of rain on the catchment of a river whose channel section is unable, at some point or points, to discharge the resulting run-off flood water. The only remedy for such cases is to discover some portion of the river section above the constricted channel in which, by erecting a suitable dam, the flood waters can, for the time being, be safely impounded, and subsequently discharged at a regulated volume. The other alternative is to remove constrictions in the river course by enlarging the cross-section of the stream, either by erecting *levees* along its banks, or by excavating the channel. There is little doubt that a well-placed flood dam is the best method of control, although levees may prove less costly and, in many cases, quite suitable. The dredging or deepening of the channel is usually liable to cause complications in the behaviour of the normal stream—particularly in the case of low-gradient rivers which traverse alluvial country.

River floods are occasionally due to the bursting of a lake-dam in the upper reaches of the river. These lakes may be due to accidental causes, such as great landslips, the débris of which slides into the valley and impounds an immense volume of water.

Although such lakes take a considerable time—sometimes several months—to fill, there comes the day of reckoning when the overflow begins. This water rapidly cuts back into the unconsolidated débris until finally an enormous volume of water is let loose. Perhaps the best known instance in India of this kind was the flood down the Alaknanda (Ganges) valley in British Garhwal, which followed the bursting of the landslip dam at Gohna, in August, 1893. Particulars of this landslip are given in the chapter on the Stability of Slopes and Cliffs, page 182. Floods also occurred in the Sutlej, after a heavy landslip near Suni, north of Simla, in 1762. (See "Ladak," by Alex. Cunningham, 1854, p. 132.)

Another Indian river which is sometimes subject to severe floods is the Indus. In this case it is known that some of the floods have been due to the damming of the upper valleys of the river, or its tributaries, by glaciers. These great ice-dams impound the water above until the pressure is more than the ice can bear, at which stage

a stupendous volume of water races down the valley. David Fraser, in his book "The Marches of Hindustan," 1907, p. 142, gives the following account of a flood in the Indus due to the damming of the Shyok river, one of its tributaries, in the wild territory north of Kashmir, and the formation of lake Nubra Tsho.

"Near its source the Shyok river is spanned by enormous glaciers that slide down from the adjacent mountains and thrust their snouts across the gorge of the river. The usual causes combine to disintegrate the ice, and it is believed that during the autumn of 1840, one of these natural bridges over the Shyok collapsed and partially blocked the flow of the river. In December and January, 1840-41, it was observed at Attock that the Indus was unusually low, and that in February and March it was even fordable. Although the melted snow in April increased the volume of water, there was still so marked a decrease in the usual quantity that it was assumed something was happening in the upper reaches. And, indeed, 800 miles upstream there was in preparation a cataclysm of terrible and unprecedented proportions. The lake which formed on the upper side of the collapsed glacier has been traced and found to measure 12 miles in length and half a mile in breadth, with a depth of 400 feet close to the obstruction. Altogether it has been calculated that about 23,000,000,000 cubic feet of water was gathered behind the glacial barrier, ready to be precipitated into the practically empty bed of the river.

"In June the catastrophe occurred. A tremendous wave swept down the valley of the Shyok with irresistible force, followed the bed of that stream for 300 miles, when it plunged into the Indus and continued its progress for another 500 miles to Torbella, close to the plains of India. Having fallen 14,000 feet during a race that had lasted over two days, the wave continued its way with unabated force and swept past Attock in a wall of thick muddy water 30 feet high, submerging the fort of Khairabad, and thereafter coursing with overwhelming strength through the Punjab and Sind to the sea, a further distance of 900 miles, or 1,750 miles altogether." (For other details see "Ladak," by Alex. Cunningham, 1854, pp. 99, 100.)

The River Indus is so unique in many ways that perhaps the reader will be interested in a more detailed account of the Indus above Attock, and in the expedients used in constructing the bridge at Attock. This account is taken almost verbatim from "Ways and Works in India," by G. W. Macgeorge, 1904, pp. 383–384.

Above the site of the bridge at Attock, the Indus drains an area estimated as equal to that of Great Britain and Ireland, viz. 120,000 square miles. Rising in the elevated regions of an unexplored portion of the Himalayan range of mountains, outside British territory, the exact length of the river is unknown, but is taken to be upwards of 900 miles. Leaving the mountain ranges about 30 miles above Attock, the river traverses a plain in a broad, shallow bed, 2 miles in width;

but before arriving at Attock, and for some distance south of that place, its channel is contracted by ranges of rocky hills through which it winds in deep gorges for a distance of 90 miles, with a cold-season water surface ranging from 300 to about 1,200 feet wide. The volume of water is usually at its lowest during the winter months, from November to March, and at this time in its most constricted parts the river carries a maximum depth of water of about 30 feet. As the hot season advances, the melting of the Himalayan snows causes the water to rise an additional 20 feet, or so, by the end of May. The highest floods commonly occur during the monsoon months, when the rise of water at Attock reaches as much as 70 feet above low-water level. The river is also subject to exceptional floods of almost unlimited volume, caused by landslips or heavy accumulations of ice blocking the course of its mountain tributaries. Immense quantities of water, impounded by the barriers thus formed, are occasionally suddenly released, creating violent and unexpected floods in the main river. A flood, known to have been due to temporary impounding of the water, occurred in February, 1858, when the water rose 70 feet at Attock; and it is probable that the great flood of 1841, said to have risen over 100 feet above low water, at the same place, had a similar origin.

The Attock railway bridge presents an example of a design specially modified to meet peculiar and unusual local conditions. It was necessary to take into consideration the possible recurrence of abnormal floods such as those noted above, and it was accordingly determined to place the bottom of the girders well above the level of the great flood of 1841, or at a height of 111 feet above low water. The district of Attock is, moreover, liable to earthquakes, slight shocks being of frequent occurrence, the seismic wave being generally east and west. To meet this source of danger it was considered advisable to employ a more yielding and elastic material than stone or brick for the piers of the bridge, and to substitute an open wrought-iron framework. The wisdom of this decision was fully confirmed, even during the construction of the work; for, on the 31st March, 1883, a sharper earthquake shock than usual occurred, when it was found that the girders of the first span had moved forwards and backwards, over one inch, on the pier, and the movement was probably much greater on the higher piers, in the centre of the river, where it could not be measured. The expansion rollers placed under the ends of the girders permitted this degree of movement without causing any appreciable strain; but had these not been in perfect working order, a considerable stress would have been thrown on the piers.

GORGES.—Different explanations have been advanced at various

times to account for the origin of gorges. The opinion now generally held is that most great gorges have been excavated by the corrasive action of streams carrying silt and gravel, or by the boring or undermining power of falling water containing rock fragments.

A glacial, or rain-fed, mountain stream with a steep gradient is ceaselessly at work reducing its gradient by cutting back into the mountains, and so lengthening its course. Such streams carry enormous quantities of rock débris, and, by the abrasion of these fragments, carve out their beds, and scour into the hills until they eventually cut through the orographic axis of the range. Thus, most of the great south-flowing rivers of the Himalayas have made impassable gorges 6,000 to 10,000 feet deep through that mountain chain. The Brahmaputra appears to have cut so far back as to have gradually captured the drainage of the great, ancient Tsang Po River, which appears to have originally flowed westward through Tibet, probably to the plains of North-West India; and, by reversing its gradient, deflected it through the Assam Himalayas to the plains of Bengal. (See "A Sketch of the Geography and Geology of the Himalayan Mountains and Tibet," by S.G. Burnard and H. H. Hayden, Part III, p. 155.)

Occasionally a stream, having a considerable difference of level between its source and point of discharge, has simply cut down into soft rocks and made a deep ravine. The best-known case of this kind is that of the Grand Canyon which has been carved out by the still active Colorado River. The plateau overlooking the present river in the Colorado Canyon is in some places no less than 6,000 feet above the stream. It is known that the ravine at Pomona, near Milledgeville, Georgia, had been carved to a depth of 55 feet in the 20 years preceding January, 1846. (See Lyell's "Principles of Geology," Vol. I, 1867, p. 344.)

In regions of a steady local uplift, a stream has often been able to maintain its channel by cutting down its bed as rapidly as the rate of upheaval. It is easily imagined that if the elevational forces are sufficiently prolonged, the stream will eventually carve out a gorge in this part of its course. To such a cause is ascribed the Bhakra gorge of the Sutlej, just before this river emerges from the sub-Himalayan range. Another explanation of the origin of this gorge, and one which accounts for several gorges in other parts of the world, is that the regional uplift was quicker than the corrasive power of the stream, with the result that the waters of the stream were impounded and a lake formed. The lake finally overflowed, and the gradient of the discharging flood was sufficient to enable the stream to cut through the barrier and drain the lake, the point of steep out-fall being now replaced by the gorge subsequently excavated.

Similar in many ways to the above type of gorge is the seven-mile ravine in the St. Lawrence River between Queenstown and the Niagara Falls. In this case, however, the formation of the ravine has been directly effected by the waters undermining the massive limestone of the Falls. The clear water from Lake Erie, with practically no silt, comes with gathering velocity but little corrasion of its limestone channel, through the rapids, and pours over the 165-foot cataract of Niagara. At the base of the Falls there are strong bedded sandstones; between these sandstones and the massive limestone above there is a thick bed of soft laminated shale. The churning action of the water scours out these shales and undermines the overlying limestone until great blocks fall and are dashed to pieces. These fragments form the abrasive material with which the "boiling" waters further scour out

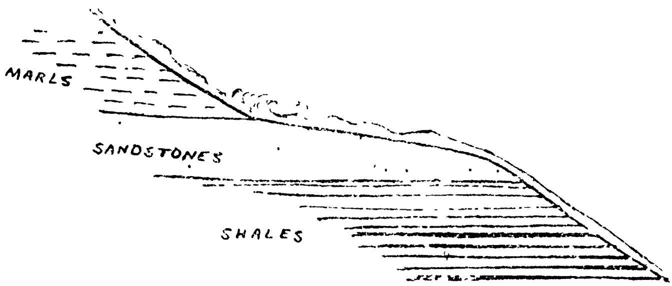


FIG. 62
Section of rapids

the shales. Careful measurements have shown that the Canadian (Horse Shoe) Falls are receding at the rate of about a yard a year. From such an estimate it may be conjectured that the retreat of the Falls from the mouth of the 400-foot deep ravine near Queenstown has taken roughly 35,000 years, if the retrograde movement has been uniform. Recent detailed estimates lower this computation, the gorge being now less than 200 feet deep near the falls. The straightness of the gorge is said to be due to the strong jointing of the rocks in the same direction as the length of the gorge.

FALLS.—The presence of rapids in a large stream of normal gradient (5 to 10 feet per mile) usually marks the position of resistent material in the river bed. This generally takes the form of a hard band of rock. In bedded rocks it would frequently mean a gentle down-stream dip of the strata (see section of rapids shown in Fig. 62).

When the steepness of the water descent is such as to necessitate the use of the term cataract, it generally implies that hard rock terminates with a steep down-stream face—either the bedded strata are steeply inclined down-stream or are vertical, or hard and soft rocks

have been brought into juxtaposition by faulting. (See section of falls due to a fault in Fig. 63.)

In some cases cascades result from the formation of "hanging valleys," *i.e.* where the lateral drainage falls into a deep valley which has been rapidly excavated by the main stream. Even in such cases

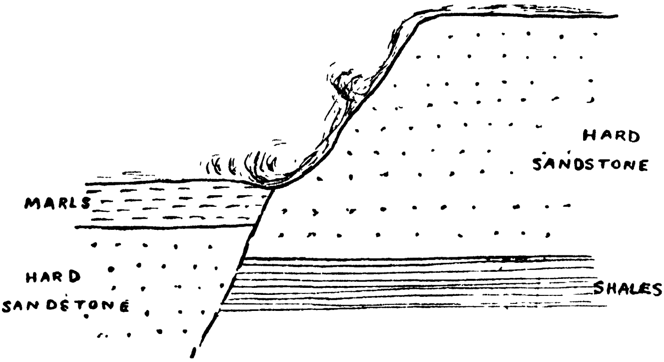


FIG. 63.
Structure of some cascades.

the structural aspect of the strata remains the same for nearly all cascades.

In those cases where the water falls over with a clear vertical drop, it is obvious that the falling water has partially undermined the rock from which the water descends. The example of the Niagara Falls

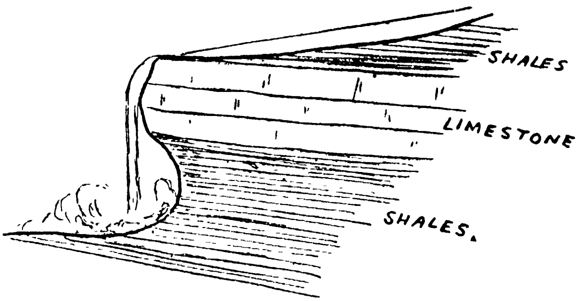


FIG. 64.
Typical waterfall section.

immediately comes to mind, and with it the structure of those falls, *i.e.* horizontal or gently inclined beds (with up-stream dips) of relatively hard rock underlaid by softer shales. (See section of falls of Niagara type due to differential erosion in strata dipping up-stream, Fig. 64.)

The same result can of course be produced by faulting, though the structure at the Falls is the same as shown in the figure above.

In cases such as the last, where the undermining action of the water must be considerable, the waterfall will gradually retreat higher

and higher up-stream, leaving a gorge, which the stream has cut, below the falls.

TERRACES.—When a large mountain lake is destroyed in the manner described above, the main stream may continue to erode its channel down the middle, or on one side, of the lake bed. In many large lakes there is a deposit of gravel and silt on the floor of the lake. Thus it may happen that some of this gravel material may be left on the sides of the stream which is flowing through the old lake floor. These residual beds of gravel and silt will constitute "terraces." Terraces of this description are sometimes found hundreds of feet above the beds of great rivers in deep valleys. They are an indication of the enormous amount of cutting that may be performed by rivers in mountainous country.

It is well known that steady, slow earth-movements are operative in various parts of the world. Large areas may be gradually depressed, other tracts may be slowly elevated. In regions of up-lift, low-velocity streams may have their gradients increased and so-called rejuvenation of the streams take place. The streams once again begin to carve out their beds, possibly in the very silt they may previously have deposited. In process of time, if a stream cuts its bed as fast as the rate of up-lift, the silt beds will appear and form river terraces on its banks. Terraces of sea pebbles and gravel are often seen on the sea-shore ; these are generally the result of a rise of the land and a regression of the sea.

BARS AND SHOALS.—Shoals are mud or sand ridges which occur in the bed of a river ; they are covered at high tides. Bars refer to those shoals which lie across the channel of a river and thus interfere with navigation. These "banks" are due to the deposition of material carried down by the river. A river deposits its load of gravel or sand or silt when the velocity of its flow is diminished. Pebble and boulder beds are generally found where mountain rivers debouch on to the plains ; gravel and sandy deposits occur lower down the river, where the gradient of the bed is less and the stream velocity unable to carry coarse material ; and the finest silt is usually precipitated in estuaries and deltas or carried out to sea. The rise and fall of the tides produce, alternately, decreased and increased velocity in the flow of a river. There is a deposition of silt in the slack water at flood tide, followed by renewed movement of the detritus during the ebb. It is for this reason, chiefly, that the tidal lower courses of big rivers have shifting sand-banks and bars. Their navigation becomes more difficult if the problem is complicated by the existence of important tributaries or the presence of ocean currents across the mouth of the river. Combinations of these physical factors are responsible for the

"sands" in many rivers and for the "bars" across various harbours (*e.g.* the James and Mary sands in the Hugli, and the bar across the entrance to Durham harbour).

In the case of very large rivers, *e.g.* the Hugli below Calcutta, it is frequently impossible actually to control the stream channel which is kept open by dredging. In other rivers elaborate protection works can often be built at a reasonable cost. The building of walls perpendicular to the banks of a stream (*i.e.* "groynes"), to prevent scour, generally produces too sudden a check on the flow of a stream. The resistance reacts by the appearance of fresh scouring, either below the "groyne" or further up-stream. Experience shows that streams are more effectively constrained by building "training walls" or embankments almost parallel with the channel, and deflecting the current gradually through successive small angles.

LAKES.—One of the most reliable sources of water supply is a conveniently located fresh-water lake. Many a perennial river with a steady flow has its source in a lake; lakes also serve as flood regulators to rivers. Thus the St. Lawrence, with its five Great Lakes, is not subject to floods to any great extent; whereas the Ohio, which has no lakes, is often flooded to heights of 50 and 60 feet above ordinary stream level. The Nile draws its water largely from Lake Victoria Nyanza but yet is subject to floods. The mystery of the Nile floods, occurring as they do in the driest period of the year, is now known. They are

"due to the rainfall on the mountains 1,500 and 2,000 miles away; this rainfall comes in the spring, and takes months to reach Egypt" (see J. W. Gregory, "Geography—structural, physical and comparative," 1908).

As the Victoria Nyanza is beyond the Abyssinian Mountains, there is no regulating lake between the mountains and the Nile; hence the rush of the run-off flow causes floods.

Naturally impounded bodies of water are to be found in almost all countries. They occupy depressions in the ground which may have been produced in one or other of several ways:

A glacier would certainly scratch out a hollow in soft rocks if a band of harder rock occurred immediately below on the down-stream side. On the retreat of the glacier, if the hollow were not filled with the débris of terminal moraines, a lake would be formed.

Similarly, a river would, if traversing soft rocks after descending rapids, corrade its bed and produce a hollow which would form a deep pool.

A side valley, if blocked by the débris of the lateral moraines of a glacier, would possibly hold a lake, as in the case of the Marjela

Sea, referred to on page 377, Vol. I, of Lyell's "Principles of Geology."

Not infrequently, a tributary stream carrying suspended matter throws a bar across the main stream, and by so doing impounds its waters, thus forming a lake; and, *vice versa*, the same action may occur with regard to tributaries or in the deltas of rivers.

In mountain valleys landslips and avalanches often choke the valley, the débris forming a natural dam which frequently results in the formation of a large lake. The lakes in the Kumaon Himalayas in many cases appear to owe their origin to landslips—the largest of these, Gohna Lake, is discussed on page 182.

Occasionally a depression is produced in the floor of a river valley by the collapse of the strata below, owing to the removal of soluble material. This is understandable in areas where brine is pumped up from salt beds; and there are numerous instances on record of the formation of "swallow holes" in limestone country. In these cases the depression may hold a lake if the soil and sub-soil material consists of impervious material such as clay.

There is abundant proof that many shallow salt lakes, such as Lake Chad in the Sahara, are, so to speak, pools left by the recession of the sea, due to regional uplift of the sea floor. The lakes of Tibet are supposed to be the remnants of a great sea, the Tethys, which once extended from China to the Mediterranean. (See Burrard and Hayden, "The Geography and Geology of the Himalaya Mountains and Tibet," 1907–08, p. 202–206.)

Elevation of the land may produce a warp across a river valley. If the stream is able to excavate its bed as rapidly as the rate of upheaval, a gorge will result; but if the rise of the valley floor is more rapid the waters will be impounded and result in the formation of a lake. The Great Lakes of North America are said to owe their origin to the warping of the land across main lines of drainage in that continent. Lakes have frequently been formed as a result of faulting; thus the lakes of Nyassa and Tanganyika lie in the sunken strip of country (due to trough faulting) which Professor J. Gregory calls the Great Rift Valley; the Dead Sea and the Lake of Galilee lie in the deep valley which marks the Akaba-Tiberias fault of Palestine; and many ponds and lakes were found on the line of faulting (the Andreas fault) which caused the terrible Californian Earthquake of 1906.

Perhaps the rarest type of lake is that which occupies the crater of an extinct volcano or the depression left by a still more violent explosion. Lonar Lake, the intriguing, vertical-sided, circular basin in the Deccan trap area of India, is said to have been the vent from which material was shot out as from a gun. The water is brackish and the

depth very shallow, but the thickness of the mud on the lake bed is not known.

In the examples given above an effort has been made to show in what ways lakes may be formed. The engineer is not so much concerned with the mode of formation of the lake as with its permanency, and this he will be able to gauge by knowing its origin. The floor of a lake may consist of exceedingly porous material, which, owing to the coincidence of the ground surface with that of the ground water, is waterlogged, and in consequence acts as an impervious stratum. If a steep-gradient stream cut back its bed and tapped the porous strata below the floor of the lake, the lake would gradually be drained. For this reason, a lake, which has been formed by lateral moraines or tributary streams or wind-blown sand, is often liable to lose its waters through the porous "bank" by which it has been formed. Lakes caused by faulting may likewise disappear by subsequent faulting if the ground water level is below the level of the lake and a channel is opened from the lake floor.

Indirect Effects of Lakes.—"Lakes tend to modify the climate of the region where they occur, both by increasing its humidity and by decreasing its range of temperature. They act as reservoirs for surface-waters, and so tend to restrain floods and to promote regularity of stream flow. They purify the waters which enter them by allowing their sediments to settle, and so influence the work and the life of the waters below" (see "Geology Processes and their Results," Chamberlin and Salisbury, 1904, Vol. I, p. 392).

TIDAL CURRENTS, WAVES AND COAST EROSION.—The movement of great masses of water towards and from the land is essentially due to the tides. In the open sea or in wide channels the tide is felt by the swell on the surface. Should the tides force themselves up constricted embankments or straits, the rise and fall of the the tide may be considerable—60 feet in the Bay of Fundy. This great rise is responsible for the rapid horizontal movements of the water—tidal currents—which sweep round the coasts. Oceanic, convection currents, such as the Gulf Stream, due to prevailing winds and to movements of water induced by differences of temperature and hence of density, assist the tidal currents in their work of erosion along the coast. These currents are so strong that they transport sand and gravel which may be lying on the sea floor. To this cause is ascribed the clean-swept rock floor which constitutes the rock surface of the continental "shelf" off the west coast of Ireland. Opinions differ as to the depth at which currents are able to move heavy objects. Much, however, depends on the extent of open sea to seaward, the nature and declivity of the floor, and the run of the coast to landward. It is known that heavy lobster pots have been disturbed at a depth of

30 fathoms off the Cornish coast. Evidence has also been obtained to show that, with a wide reach of deep water behind them, sea waves will break on banks 5 to 10 fathoms below sea level, as in the case of the banks off the Newfoundland coast. It is known that wave action is felt at a depth of 150 feet, because sand has come aboard ships over banks at this depth. Ripple marks are said to have been seen on the sea floor where the depth was 50 feet. Tidal currents are felt at very much greater depths than wave action. These currents are strongest along continental slopes and among islands and submerged ridges in oceanic situations. Although such currents are thought to be restricted to depths of 1,000 feet, it is known strong currents exist at the Azores at 2,600 feet; similar motion of the sea bed has been detected at 6,000 feet off the coast of Ireland, and to as much as 12,000 feet in the tide-swept straits of the Canary Islands.

Normally, waves are due to winds, the movement of the surface water being circular in a vertical plane parallel with the direction of the wind. The tidal pressure on a gently sloping shore naturally causes the water to bunch into waves if a wind is blowing; the waves get shorter and steeper as the shore is approached; until finally the wave breaks either on the shore or at a point some distance from it. The oscillating movement of the water, although producing waves upwards of 400 feet long and 50 feet high—crest to crest and crest to hollow—in the open sea, is much less in shallow water. However, judging by the experience gained in salving the Laurentic gold, during strong gales, the waves which come shoreward with the full force of an open sea behind are powerfully felt at a depth of even 20 fathoms.

"*The Laurentic Gold.*—The White Star liner Laurentic, which sank in 1917 off the west coast of Ireland, a vessel of 14,000 tons, which had been acting as an auxiliary cruiser, was lost in a spot exposed to the full fury of the Atlantic, in 20 fathoms (120 feet) of water.

"The work was done from the Admiralty salvage vessel Racer, 1,000 tons. Lt.-Commander E. L. B. Damant, R.N., himself a champion diver, was in charge.

"Commander Damant gave a *Daily Mail* reporter the following first full account of the salvage work:

"When we first started to work, immediately after it was sunk, the Laurentic lay on its side at an angle of 60° from the vertical. Using explosives, we blew in a door in the side of the ship near the strong-room.

"The foreman diver, Warrant Shipwright Miller, went down a transverse passage, and eventually reached the strong-room in the middle of the ship. He unscrewed some nuts from the hinges and had the strong-room open in a few minutes. Most of the gold then lay before him in boxes.

"It was very difficult to remove these boxes of gold. The diver

had to crawl up a steeply-sloping passage in pitch darkness, pushing a heavy box before him, and occasionally lifting it over obstacles.

"On the first day were moved one box and on the following day three more.

"Then a gale blew up from the north and lasted a week, during which pieces of decking and other débris were washed on shore, showing that something had happened to the Laurentic.

"When the sea subsided and it was possible to send a diver down he found that the whole ship had collapsed like a pack of cards, driving the decks out sideways. This had been caused by the enormous pressure exercised by the action of the waves deep below the surface.

"There was no hollow space in which men might crawl about, and we had to cut a way right into the crumpled ship with explosives.

"Altogether since the beginning of the operations we have removed 3,000 tons of material. In the remaining part of 1917 we recovered about £1,000,000 worth of gold.

"In 1919 the work was resumed, and some gold was recovered. In 1920 and 1921 we were very unlucky. When the ship collapsed the gold was divided into two sections. The first lot was comparatively easy to recover. The second consignment, however, was buried beneath about 10 feet of sand and debris, consisting of broken-up fragments of the ship and its fittings, including such things as berths, baths, wash-basins and tables.

"The divers worked in a jagged crater in the middle of the ship, and to remove the sand they had to scoop it into sacks with their hands. The sand was made quite hard by the action of the waves, and the divers loosened it with a fire-hose pipe let down from the Racer.

"The diver squirted the jet of water into the sand, thereby loosening it, and as he did this he pushed his hand into the loosened sand to feel for the gold.

"The men crouched or lay down on the sand, scooping it into sacks and feeling for the gold. Sometimes at the end of several days of work they would have their finger-nails worn down almost to the quick, and the tips of their fingers soft like sponges. They would not wear gloves.

"In 1922, 1923, and 1924 we made good progress, and at the end of that year there was less than one per cent. of the gold in the wreck. The sand was then gaining fast on the divers and the work had to be abandoned.

"Throughout there was not one accident.

"Owing to the high compression a diver could only work at the bottom about one half-hour at a time. It took him about half an hour to come to the surface so that the pressure in his suit might be reduced by stages.

"During the operations we had a number of cases of high-compression sickness. These were treated by putting the affected man at once into the recompression chamber on board. He was there put under a high air pressure again, and very soon felt better.

"Some of the bars of gold recovered were bent right round into a 'U' shape, while others had pebbles driven hard into them—and also half-crowns."—*The Daily Mail.*

On a shelving sand or gravel shore during relatively calm weather the incoming waves may begin to move the loose material to an appreciable extent at a depth of 10 fathoms, but more commonly this action is observed where the depth is 5 fathoms or less. The direction of movement varies with the direction of the currents and the declivity of the floor. If it is shoreward, the sandy gravel on a gently rising shore may be piled up to form a ridge (a storm beach dam) some distance from, and parallel to, the shore, and may result in the development of a lagoon. The lagoon known as the "Fleet," behind the Chesil Bank, is an example of this kind. The lagoon at Venice is another example, but here the ridge is not complete. The Zuider Zee, on the other hand, is due to the storm beach dam being subsequently breached. If the seaward slope of the gravel shore is somewhat steep, the loose material is piled up on the shore to form a true storm beach of the type of the Chesil Bank near Abbotsbury. The waves rush up these gravel slopes, piling the material in front of them until the fury of the rush of water is checked by the bank they have themselves built up. In many cases the waves strike obliquely, and consequently cause the gravel and shingle to travel in their direction, *i.e.* along the coast. If the supply of gravel, etc., can be maintained, a protective apron is thus built up. A gravel or shingle beach of this description is therefore one of the finest protections a coast may have against erosion by the sea waves and currents. The removal of such gravel from such a position should therefore be strictly forbidden. The travel of the shingle should be retarded by the construction of groynes. The type of groyne is a matter for the engineer to settle, but it must be stated that too sudden a check of the gravel may result in scour further up or down the coast, and might possibly lead to the gravel beach itself being swept away. It is fallacious to think that erosion can be entirely stopped. The operating forces are so powerful and ceaseless that the best that can be hoped for is a reduction of the speed of erosion. In protecting shingle beaches, there is wear of the pebbles, and this must be replaced, either naturally or artificially.

The question of coast erosion was very carefully considered by the Royal Commission on Coast Erosion (1907). In the evidence collected, very divergent opinions were expressed on some questions of submarine erosion. On one hand it was said that sand and shingle once carried into deep water never returned. W. H. Wheeler gave a case of a steamer which was sunk at the mouth of the Gironde River (France). "When they came to examine it, they could find nothing of the steamer at all; then they came at a different state of the tide, and she was fully exposed." This showed that there was a forward and backward movement of the sand below the water mark, probably

due to tidal currents as distinct from wave motion. The tidal currents are felt right to the bottom of deep water and may transport and scour and deposit silt at depths exceeding 30 fathoms, possibly at more than 100 fathoms; surface waves, however, are thought to be very slightly felt at even little depths. Sir G. B. Airy (*Cyclopædia Metropolitana*, Div. II, Vol. III, 1845, p. 294) says:

"When the depth is great in comparison with the length of the wave as in the case of ordinary waves in the open sea), the motion of the water at any great depth is wholly insignificant in comparison with that at the surface. The following rule may be convenient. As the depth below the surface proceeds in arithmetical progression, the motion diminishes in geometrical progression, and at a depth equal to the length of the wave the motion is diminished to 1/535.4 of that of the surface."

Lord Rayleigh, quoted in the *Trans. Devonsh. Assoc.*, Vol. XIX, 1887, p. 504:

"For each step downward of x/8 (x being the wave length) divide by 2.2."

W. H. Wheeler, in his book, "The Sea Coast," 1902, says:

"The depth to which the agitation extends is in the ratio the length (of the wave) bears to the height. . . . Any movement of sand, stones, and shells that takes place in water of considerable depth is due to tidal currents, and not to wave action. . . . When there is considerable wave motion on the surface of the sea, at a depth at which divers are able to work the water is found to be motionless."

The direction of the wind is an important factor with regard to the movement of the beach material. An off-shore wind appears to be able to bring sand from the sea bottom to the shore from a depth of 6 fathoms, while an on-shore breeze actively cuts down the beach and carries the sand seaward. The explanation of this unexpected phenomenon is that (1) the translatory movement is checked and the original circular movement is restored by an off-shore wind, with the result that this break effect causes a kind of deep in-shore current which brings the sand and shingle to the beach, and (2) the in-shore wind produces flooding of the shore with a deep out-flowing current or undertow which carries away the beach material.

When a wave impinges obliquely on a beach, the out-run or undertow is almost at right angles to it. A succeeding wave, acting on a particle which has been carried up and down the beach by the previous wave, will again drive it up the beach; the actual travel of the particle will be a sort of saw-tooth motion, but a steady movement along the beach with each zigzag. In this way shingle may travel along a shore by wave action alone. Tidal currents assisted by waves, *e.g.* flood tide and an in-shore breeze, accelerate the travel of shingle, and, if

the supply of shingle is inadequate, may lead to rapid erosion of the shore which has been thus denuded.

Turning to those shores where the waves wash against bare rocky cliffs and currents sweep along their unprotected base, the natural agencies of atmospheric denudation are actively assisted by the scour and wash of the sea. Any material that slips down is washed away, and the slope above maintained at an unstable angle. It is not easy to suggest how this erosion might be most effectively checked ; much depends on local circumstances—the height of the cliff, the nature and structure of the rocks composing it, the declivity and extent of the foreshore, the force and direction of the waves and currents, etc. If a storm beach dam could be established by dumping debris at the right distance from the shore, a very effective barrier would be made. Failing this, resort should be made to the production of a normal storm beach of pebbles, stiffened with groynes, at the foot of the cliff. Sea walls are costly and seldom effective except in deep water, and then only if their foundations are secured against the scouring action of receding seas.

From the above it is clear that a submarine cable, brought ashore on such coasts, must be subject to great abrasion by the to and fro motion of the water and loose gravel. Such cables should, if possible, be deeply buried or well armoured—at least as regards the section which lies below high, and above low, water tides.

A great number of earthquakes originate below the bed of the ocean. These frequently affect the shore lines, first by the destructive effect of the waves produced, and finally by the resulting emergence or subsidence of the land. From soundings, there is also, often, evident a corresponding alteration of the ocean bed. There are also frequent instances when telegraph cables have snapped owing to the strain put upon them by the altered configuration of the ocean bed. In other cases telegraph cables have been found injured by slides of débris—apparently due to great masses of fine sediment slipping down the slopes of the continental shelves, such as exist off the coast of Japan and elsewhere.

CHAPTER XVI

SURFACE WATER SUPPLIES

GENERAL REMARKS.—The chief sources from which surface water is obtained for domestic or irrigation requirements may be grouped as follows :

Running Water from springs, streams, and rivers, procured directly or supplied through conduits, *e.g.* pipes and canals.

Stationary Water from lakes and ponds or provided from reservoirs and tanks.

In all these cases the essential factor is rainfall. If the rainfall is good, the supplies remain normal ; but a failure of the rainfall generally leads to water difficulties and, if the source of supply is of small capacity, probably to water shortage. In Chapter XIII of this book an endeavour was made to elucidate the problems connected with the precipitation and distribution of rainfall. The subject of rivers and streams was discussed in the previous chapter, but the subject of canals is treated below. Similarly, the occurrence of Lakes was described in Chapter XV, but the subject of reservoirs and tanks remains to be dealt with in this chapter.

Springs are one of the safest sources of water supply. Occasionally, however, such waters are not potable, owing to the fact that this water has percolated through strata contaminated with injurious substances. Beeby Thompson has very ably discussed the questions involved in utilizing springs which, through some accident or neglect, have become contaminated. (See "Emergency Water Supplies," 1924, pp. 25–31.) He gives the experiences of our Expeditionary Force in Salonika with regard to abandoned fountain heads of the Roman period. These were found to be some distance from the actual supply spring of the existence of which the local inhabitants appeared to be unaware. The origin and behaviour of Springs belongs more fitly to the subject of Underground Water, and will be more fully dealt with under that heading in the next chapter.

Mention must here be made of the dew-ponds of the South Downs of England. Even to-day such methods of procuring small supplies of water, chiefly for watering cattle, are in use, but the subject is more

of theoretical than of practical interest. It is thought by some that the British camp on Cær Caradoc, when besieged by the Romans about 50 A.D., obtained a great deal of its water from dew-ponds on that isolated hill. It is a pretty story, for others believe that Caractacus surrendered because he was compelled to do so owing to a shortage of rain water.

Snow and rain-water tanks are still widely used very effectively for procuring water for domestic purposes. As Thompson says, Aden still to some extent depends on occasional rainfalls to fill the " Tanks " some miles inland from that arid port. He also mentions use of the *Tebeldi* tree, which is hollowed out for the purpose of storing water during the rainy season in the Provinces of Kordofan and Darfur in the Sudan. Nor does he forget to mention the storage of snow in underground chambers by the natives of the Ural Province of Russia as the only source of supply in the hot months in parts of that region. In Warburton's day some of the tribesmen of the Khyber Pass found time during the winter months to dig deep pits high up a mountain-side on which snow had fallen, and to fill these pits with compressed snow. Their object was to have it, not for domestic use, but for the cooling of *sherbat*—a drink much appreciated in the hot months. It is said that this iced *sherbat* was available in the Peshawar bazaar even in May and June. However, with the erection of an ice factory at Peshawar, and the construction of the Khyber railway to the Afghan frontier, this industry has practically ceased to exist.

CANALS : IRRIGATION AND NAVIGATION.—Most canals have more or less straight channels. These artificial waterways are usually designed for one of two purposes—irrigation or navigation.

SOME NAVIGATION CANALS, such as the Suez Canal, have an unhampered waterway throughout their course ; others, such as the Panama Canal, are fitted with locks for the purpose of negotiating the country through which they pass. The objective aimed at in a navigation canal is to avoid currents, and the water should be as still as possible, so that navigation may be equally easy in either direction. Such canals require little or no replenishment other than that necessary to meet evaporation and absorption losses and the diminution caused by using locks.

IRRIGATION CANALS, on the other hand, are true artificial streams. They are generally constructed on the highest ground possible, in order to be able to supply water to waterless watersheds. Their gradients are so designed that the current in the canal causes little or no scour ; their channels are made to discharge the maximum volume of water with the least friction ; and their take-off and alignment aim

at giving them "command" of the greatest possible area to be irrigated.

As seen from the above remarks, Navigation and Irrigation Canals have certain conflicting requirements. For this reason it is generally inadvisable to use one canal for both purposes. The construction of a navigation canal is similar to that of an irrigation canal, in many respects, from a geological point of view. It happens, however, that far more publicity is given to the ship canal than to the less ostentatious, but usually more profitable, supply canal.

Irrigation engineers classify their canal systems into two chief varieties—perennial canals, or those fed from perennial streams, lakes or reservoirs; and intermittent (including inundation) canals, which are fed by deflecting the entire discharge of intermittent streams, or the flood discharge, above a certain level, of perennial rivers. In all cases of river-fed canals there is an interference with the surface drainage of the country—the river discharge being wholly or partially eliminated at the head-works of the canal. In the case of the Upper and Lower Ganges perennial canals in India, the quantity taken is no less than 13,200 cusecs for a command area of upwards of 4 million acres. D. G. Harris ("Irrigation in India," 1923, pp. 99–100) says:

"It is difficult to describe what its irrigation works have meant to India. To say that 28 million acres are, or that 40 million acres will in the near future be, irrigated conveys but little idea. As has already been stated, the area irrigated in any one year is not a fair criterion, as the benefits of irrigation extend far beyond this, and for every acre irrigated another acre or acre and a half is irrigable and will receive water in succeeding years while that previously irrigated lies fallow for a time or is sown with some drought resisting crop. It is not too much to say that the Government works render over a 100 thousand square miles of precarious country, which otherwise would be in continual dread of famine, certain of their crops, and that this area will be increased by 50 per cent. when the great projects now under construction or about to be constructed are finished. Of this area, huge tracts would, but for the canals, be barren waste. In 1920–21 the value of the crops irrigated was no less than £156 million, exactly double the capital cost of the works. Most of these crops could never have been brought to maturity without irrigation and a considerable proportion of them was raised on land upon which, but for the canals, not so much as a blade of grass would grow."

In canal projects due consideration is naturally given to the shrinkage of the rivers below the intake of the canals.

The fall in the ground water-level and the consequent inconvenience caused to villages drawing well-water in the vicinity of the river below the head-works of the canal are, however, seldom fully allowed

for. These effects are felt gradually but increasingly and, finally, might result in the abandonment of the villages concerned.

The difficulties encountered by engineers in the construction of canals in hilly country are sometimes not thoroughly appreciated by the public they serve. Perhaps one of the most striking examples of this kind is that of the Swat river canal in the North-West Frontier Province of India. The following extract will help to a clear understanding of a little-known piece of work which deserves greater publicity. The Swat River Canal (see *Imperial Gazetteer of India*—North-West Frontier Province, 1908, p. 120) is for perennial irrigation work in the Peshawar district.

"The canal takes off from the right bank of the Swat river at Abazai and irrigates about 155,000 acres. The place of a weir is taken by a natural reef stretching across the river below the head regulator. The regulator has seven openings of 6 feet each, and is protected at each end by fortified blockhouses—forming one of the chain of frontier posts garrisoned by the border military police. The main channel has a width of 31 feet and a depth, when full, of 7.35 feet; it can carry a supply of 865 cubic feet per second. In a total length of 22½ miles there are no less than 21 drainage works, which carry under or over the canal the water of the numerous torrents that intersect its course. These are for the most part crossed by massive stone aqueducts, and the canal banks for some distance above and below these crossings are of a great height. About 186 miles of distributary channels have been aligned on the watersheds between the torrents, the most important being the trans-Kalpani distributary, which has a discharge of 94 cubic feet per second, and a length of nearly 14½ miles, and in which there are fourteen drainage works of importance.

"The tract commanded by the canal is that portion of the dry, sparsely populated Yusufzai plain which is bounded on the north by the canal itself, on the west and south by the Swat and Kabul rivers, and on the east by the Mokam nullah, a tributary of the Kalpani. The country rises so rapidly on the north of the canal up to the foot of the hills that it cannot be brought under command. The canal tract itself is cut up by innumerable nullahs running generally from north to south, and carrying the drainage from the hills on the north to the Swat and Kabul Rivers on the west and south. The great cost of the canal was due to the difficulty of taking it across these channels, some of which are of great size.

"The main canal was opened in 1885, and the trans-Kalpani distributary in 1899. The Naushahra minor, a channel irrigating two grass farms near Naushahra, was constructed in 1901. The area irrigated in both harvests during the three years ending 1901–02 averaged 161,000 acres, and in 1903–04 it was 159,000 acres. The total capital expenditure to the end of March, 1904, was 41.4 lakhs. The canal was originally sanctioned as a protective work, no profit being anticipated owing to the high cost of construction. The whole accumulated interest charges were, however, paid off in fifteen years,

and the net revenue in 1903–04 (Rs. 4,57,000) exceeded 10 per cent. on the capital expended. The canal has thus become a remunerative investment to Government, besides contributing in no small degree to the peace of the border."

It failed, however, to touch the part of the Yusufzai between the main channel and the border hills to the north where water was badly needed. Subsequently a tunnel was driven through the Malakand range to tap the Swat river near Chakdarra. As this river is fed from the snows, it attains its greatest volume in the summer months, and thus water is abundantly obtained just at the time it is most needed. The water from the Malakand pressure tunnel is led to Dargai, from which place a canal has been made with branches running west to Abazai, the head of the parent canal, and south-east to the Indus at Pehur and the Kabul river at Jahangira. These distributary channels practically command the whole of the Peshawar district, north of the Swat and Kabul rivers, which had not already received canal irrigation —an area of about 600 square miles.

The following details of the Sirhind Canal, taken from "Ways and Works in India," G. W. Macgeorge, 1904, p. 140, are also of great interest.

"The tract of country lying between the upper waters of the Jumna and Sutlej rivers contains the watershed or ridge line of division between the Indus and Ganges basins. This watershed lies much nearer the Jumna than the Sutlej, and the space between it and the latter was once watered by the Ghaggar, the ancient Saraswati, a river which . . . formerly flowed through the heart of the country, from the mountains to the Indus, near Rori, in a direction almost parallel with the Sutlej; but its vast lower beds, locally known by the names of 'Hakra' and 'Sankra,' have long been dry hollow wastes.

"The water in the modern (Saraswati) river, even after the heaviest rainfall, is soon swallowed up in the ever-encroaching desert sands to the southward. In this almost rainless region, comprising the districts of Ludhiana and Ferozepore and the Native States of Puttiala, Jind, and Nabha, west of the Ghaggar, the want of water for purposes of cultivation was extreme. In the year 1840 Captain (afterwards Sir William) Baker took a line of levels across the country from Karnal to Ludhiana. He found that the greatest elevation of the watershed between the Jumna and the Sutlej (lying comparatively near the former river) was 68 feet, and after further preliminary investigation he ascertained the perfect feasibility of conducting water from the Sutlej into an immense culturable area, then almost a dry desert. . . . In the year 1869 the matured project for the existing 'Sirhind Canals' was fianlly settled.

"The Sirhind Canal system as carried out consists of a short trunk canal drawn from the Sutlej at Rupar. At the forty-first mile a division of water is made; one main branch extending westwards to Ferozepore, mainly for the supply of water to British territory, and

another main branch south-eastwards to Puttiala, principally to supply the wants of the Native States of Puttiala, Jind and Nabha. . . . The trunk and main branches to Ferozepore and Puttiala respectively are navigable. . . .

"As usual in the case of canals drawn from rivers not far from where they issue from the mountains, the heaviest portion of the works on the Sirhind Canals lies in the first few miles from the head, where the channel has to cross several mountain torrents which intersect the Sutlej valley. A masonry dam or weir is constructed across the Sutlej nearly opposite the town of Rupar, and just above the weir a regulating bridge crosses the commencement of the main canal, 200 feet in width. The canal is carried through a hill spur in a cutting 45 feet deep in the highest position, and with an average depth for about nine miles of 28 feet. The cross drainage of the valley is conveyed over the canal by two large masonry over-passages. Prison labour was very largely employed on this portion of the works.

"The total length of main-line and branches is 542 miles with 4,385 miles of distributing channels. 189 miles of the canals are navigable, of which 143 are British and 46 are in Native States. The system commands an irrigable area of over 800,000 acres, or 1,250 square miles of cultivation."

THE UNDERGROUND WATER BELOW CANAL BEDS.—When a canal is cut through rocks in which the permanent ground water-level is below the designed water-level of the canal, percolation will take place from the canal bed to this ground water until it is raised to the same height as the water in the canal. All unlined canals which are excavated in relatively porous ground above the permanent ground water-level will be subject to considerable leakage for the same reason. There will be a large initial loss until the ground water-level is more or less stabilized and, owing to the elevated position (usually on a watershed) of the canal cutting, there will, in all probability, be a continual loss to compensate for the evaporation which will occur from the surface of the waterlogged strip of country on each side of the canal. The width of these marginal strips will naturally depend on the declevity of the ground surface away from the canal.

At the time that the Suez Canal was being constructed it was thought that the channel would fill rapidly (six days at most), even though the water-level in the several lakes on the alignment was appreciably below mean sea level. When, however, the seaward entrances were dredged and access given to the sea at each end, the canal filled exceedingly slowly (six weeks, according to report). This was due to the large volume of water which percolated into the sand and raised the ground water-level for a considerable distance on each side of the canal. In this instance both the ground water and the canal water are heavily charged with sodium chloride and various other salts. The sub-soil water in the vicinity of the canal has naturally

become similar, but, owing to the steady evaporation which is in progress, the salinity of the sub-soil water in the strip on each side of the canal is steadily increasing and the soil of this low ground is becoming yearly more impregnated with saline matter.

The deterioration of cultivable land in the vicinity of certain canals in Northern India, as a result of the concentration of sodium carbonate in the soil, is due to a similar *modus operandi.*

There is also another aspect of the case. In areas where the underlying alluvial strata is impregnated with saline matter, it is unwise to interfere with the surface drainage without a careful consideration of the results which may follow such an operation. Suppose, for example, a dam were built across a stream and the run-off flow of the stream impounded, leakage below the dam might continue to maintain the underground stream-flow and shallow wells in the stream

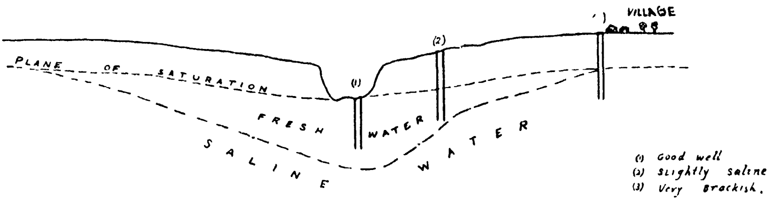


FIG. 65.
River section in alluvium.

bed would perhaps not be affected ; if, however, the dam foundations effectively prevented leakage, the underground flow would diminish, saline water would gradually return to the stream bed, and villages lower down-stream would find that their shallow stream-bed wells were becoming contaminated with saline water. In process of time, the contamination would render the water of down-stream wells as brackish as that of those wells which are away from the stream (see Fig. 65). The cleansing action of centuries of percolation would thus be rapidly undone. If those villages, below an irrigation dam, which had been dependent, during dry periods, on the shallow wells in the bed of the stream, were provided with a pipe supply and the impounded water was led away for irrigation purposes elsewhere, it is possible that the accompanying change in the direction of sub-soil drainage might not be detected. However, the engineer will at least know what to expect, although he may fail to appreciate the full distance down-stream along which the sub-soil drainage will become affected.

THE FORMATION OF "ALKALI" SOILS.—The term "Alkali" has been applied by irrigation engineers and many agricultural chemists to any salts which, when concentrated in the soil, are injurious to cultivated plants. Chemically, in its strictest sense,

the term refers to a salt with a basic reaction. However, long usage has given the term a definition which is well understood, and in this restricted sense the word alkali is used in this book.

It is well known that in the processes of weathering, large quantities of soluble matter are leached from various rocks and carried into the rivers. Messrs. Chamberlin and Salisbury (see "Geology: Processes and their Results," Vol. I, 1904, p. 107) have given (Murray's data) the amount of mineral matter carried in solution in average river waters:

Constituents in solution.	Tons in a cubic mile of average river water.
Calcium carbonate ($CaCO_3$)	326,710
Magnesium carbonate ($MgCO_3$)	112,870
Calcium phosphate ($Ca_3P_2O_2$)..	2,913
Calcium sulphate ($CaSO_4$)	34,361
Sodium sulphate (Na_2SO_4)	31,805
Potassium sulphate (K_2SO_4)	20,358
Sodium nitrate ($NaNO_3$)	26,800
Sodium chloride (NaCl)	16,657
Lithium chloride (LiCl)	2,462
Ammonium chloride (NH_4Cl)	1,030
Silica (SiO_2)	74,577
Ferric oxide (F_2O_3)	13,006
Alumina (Al_2O_3)	14,315
Manganese oxide (Mn_2O_3)	5,703
Organic matter..	79,020
(Average river water) Total dissolved matter ..	762,587 tons

The dissolved constituents in certain rivers vary greatly from the above averages both in type and quantity. Thus it is seen—analysis on page 298—that the waters of the Hugli, near Calcutta, contain carbonates of calcium, magnesium, and sodium in large percentages, and very little sodium or other chlorides. The waters of the Indus, near Sukkur, show similar features, although there are considerable percentages of chloride salts and a very marked amount of silica compared with the total constituents in solution.

In contrast with the constituents in solution in average river water, the composition of sea water is interesting. "Every 1,000 parts of sea water contains about 34.40 parts, by weight, of mineral matter in solution (Dittmar, *Challenger Reports*, *Physics and Chemistry*, Vol. I, p. 204). Expressed in terms of tons per cubic mile of sea water, the composition is as follows:

		Tons per cubic mile.
Chloride of sodium (NaCl) ..	..	117,434,000
Chorlide of magnesium ($MgCl_2$)	..	16,428,000
Sulphate of magnesium ($MgSO_4$)	..	7,154,000
Sulphate of calcium ($CaSO_4$) ..	..	5,437,000
Sulphate of potassium (K_2SO_4) ..	..	3,723,000
Bromide of magnesium ($MgBr_2$)	..	328,000
Carbonate of calcium ($CaCO_3$) ..	..	521,000
(Sea water) Total dissolved matter	..	151,025,000

From the above two tables it would appear that the river-borne carbonate of calcium must be largely precipitated in sea water, the magnesium carbonate converted into magnesium *chloride* and sulphate, and the sodium sulphate converted into sodium chloride.

The transformation of soluble salts, which are leached from decaying rocks by percolating water and carried into lakes with an enclosed drainage, is noticeable in the waters of many inland lakes. These saline lakes, which occupy depressions in arid or semi-arid regions, are classed as "salt," when they contain chlorides of sodium and magnesium, and sulphates of magnesium and calcium—they approach the composition of sea water. "Bitter" lakes, on the other hand, contain much sodium carbonate (and bi-carbonate), as well as sodium chloride and sulphate, and sometimes borax. If these lakes are undergoing desiccation, the relatively insoluble constituents in them will crystallize out and be precipitated, while the most soluble constituents will remain dissolved in the lake water. The dissolved constituents in the waters of Lonar Lake (Deccan, India) were found by Dr. W. A. K. Christie (see *Rec. Geol. Surv. India*, Vol. XLI, Part 4) to contain the following elements :

Chlorine (Cl) ..	.. ..	34.18 grains per litre
CO_3 as carbonate	.. ..	12.60 ,, ,, ,,
CO_3 as bi-carbonate	.. ..	2.19 ,, ,, ,,
SO_4	.. ..	1.24 ,, ,, ,,
Sulphur (S) ..	.. ..	0.101 ,, ,, ,,
Silica (SiO_2) ..	.. ..	0.34 ,, ,, ,,
Calcium (Ca) ..	.. ..	0.01 ,, ,, ,,
Potassium (K) ..	.. ..	0.09 ,, ,, ,,
Sodium (Na) ..	.. ..	33.21 ,, ,, ,,

The predominance of soluble chloride and carbonate of sodium is evident. This case is particularly interesting, because the lake is situated in the heart of the basaltic region of the Deccan, and lies in a depression of enclosed drainage of small extent. It is known that the basaltic lavas contain large percentages of calcium and magnesium. The presence of tufa shows that the calcium is being removed from the rock and deposited on the banks and bed of the lake as calcium car-

bonate, and yet there is none of this substance in the " bitter " waters of the lake.

Turning from these superficial considerations, we find that, in the saline subsoil waters in many arid regions, the commonest soluble salts are the chlorides, sulphates, carbonates, and nitrates of sodium, potassium, magnesium, and calcium. It is therefore concluded that in such cases the alluvial material in which these saline waters occur must have been deposited in an arm of the sea which was subsequently cut off and dried, or in the bed of an inland lake which was subject to an evaporation loss greater than the rainfall flow into the basin.

If this saline underground water is close to the surface of a hot, rainless region, it is almost certain that the water will be drawn into the soil by capillary action ; it will then be evaporated from the soil by the heat of the sun and leave behind the salts it contained. In process of time the surface of the ground will either become encrusted with the accumulated salts, or these salts may cement the undersoil into a hard impervious layer (hard-pan).

The encrustation or efflorescence will be very noticeable if it is white, whereas the " hard-pan," usually being a few inches below the surface, will not be so readily observed. In the former case, although appearances might lead one to suppose the land heavily contaminated, it is possible that the vegetation and crops may not be seriously affected. On the other hand, where there is little sign of surface efflorescence, the cultivated vegetation may sicken, and certain characteristic plants indicative of alkali, may make their appearance.

An examination of the salts in the soils of the worst " alkali lands," *i.e.* where cultivated plants will not grow, generally results in the discovery of appreciable percentages of the more soluble carbonates ; these salts have consequently been considered as the most injurious to crops. The worst of these very soluble carbonates is said to be carbonate of sodium—commonly known as " black alkali " (*reh* or *kallar* in India). If, owing to too low a rainfall, the yearly wash of the rains is insufficient to remove the alkali which is deposited in the soil, an accumulation will take place and the land will become sterile.

The investigations of the " Reh " Commission in India (see " Investigation of Usar Land in the United Provinces," by J. W. Leather, 1914, p. 88) are thought to have

" brought out the fact that under the ancient systems of agriculture in India there was very little increase in the amount of soluble salts at the surface, but, with the construction of large modern canals and the application of unnecessarily large quantities of irrigation water, the increase in alkali was very rapid " (see also " Soil Alkali, its Origin, Nature and Treatment," by F. S. Harris, 1920, p. 14).

It is known that by conducting water in an unlined canal along a water-shed and through porous ground containing saline sub-soil water, the ground water-level will be raised by the leakage from the canal. In this way, in an endeavour to irrigate one area, another may be exposed to the danger of alkali formation. A similar rise of the ground water will occur on the down-stream side of an over-irrigated area, particularly if the ground is very gently inclined and not intersected by deep water courses, the cause being that the surplus water rises to the surface on the lower slopes of the areas adjacent to the water-shed which is being heavily watered. If the underground water is saline, the processes of caillary action, evaporation, and concentration discussed above are likely to be repeated in these areas, with the result that a *second* area may be rendered barren by the irrigation from a single canal system. Thus it is seen that under certain particularly unfortunate physical conditions, *i.e.* a combination of porous ground, in the region of the main feed canals, and saline sub-soil water, the irrigation of one area may lead to the development of alkali in two others, one *above* and the other *below* the tract which is being reclaimed.

Observations in Egypt have shown that during the flood flow of the Nile there is a considerable leakage of water from the river into its banks. With the fall of the water-level in the river there is an appreciable return flow to the river. (See " The Movements of the Sub-soil Water in Upper Egypt," by H. T. Ferrar, *Egypt. Survey Dept.*, Paper No. 19, Cairo, 1911, p. 74; also " The Chemistry of the River Nile," by A. Lucas, *Egypt. Survey Dept.*, Paper No. 7, Cairo, 1908, p. 37). W. F. Hume (" Geology of Egypt," Vol. I, 1925) says :

" of the effect of canals on alkali lands, whenever a district is irrigated from a high level canal without adequate provision being made for efficient drainage, invariably the low-lying fields will be converted into swamps, the general level of the subsoil water will be raised, and the injurious salts brought to the surface. As an example of this may be mentioned a strip of land in the Wadi Tumilat (the land of Goshen) from Abbassa to Kassasin due to the construction of the high-level Ismailia Canal in 1863."

REMEDIAL MEASURES.—Attention has been directed to the evident relative solubility of the various salts contained in saline waters, and the soluble carbonates were particularly mentioned—specially carbonate of sodium. Carbonate of calcium (and bi-carbonate) is easily precipitated as crystals and aggregates in the soil and sub-soil as calcareous nodules (kunkur). This material has not been found to be injurious to crops, nor does the sulphate of calcium appear to be harmful to cultivated plants. In consequence of this, it is naturally thought that the poison is carbonate of sodium—a very soluble salt, and presumably one which should be easily decomposed or washed

out of the soil. However, the opinion has gained ground that, because the percentage of sodium carbonate in sub-soil water is occasionally small and apparently too small to account for the rapidity with which it becomes concentrated in the soil, there is some chemical interaction between the calcium carbonate obtained from the saline sub-soil water and the sodium nitrate previously present in the soil. To the presence of nitrogen-fixing bacteria, the occurrence of sodium nitrate of organic origin, and the activity of certain plants, are ascribed these chemical changes whereby a relatively insoluble salt is decomposed into a more soluble substance.

V. M. Mosseri (" Les Terrains Alcalins en Egypte et leur traitment," *Bull. Inst. Egypt*, Caire, Serie V, Tome V, 1911, pp. 53–70) emphasised the importance of sodium carbonate and pointed out the danger of the bi-carbonate because of its ready conversion to the carbonate. This salt deflocculates the clay and prevents coagulation, so that the soil becomes compact and impermeable—0.08 per cent. of Na_2CO_3 in a heavy clayey soil is sufficient to render the soil absolutely useless.

The following data by Mosseri appear to have been accepted for arable lands :

Sodium carbonate	0.05 per cent. minimum toxicity. 0.10 per cent. maximum limit of tolerance.
Sodium sulphate Sodium chloride	0 to 0.25 per cent. not injurious. 0.25 to 0.50 per cent. injurious, but not fatal. 0.50 per cent. maximum limit of tolerance.

There are several varieties of plants, usually salt-grass, salt-scrub, etc., which do not grow except on soil contaminated with alkali. Some of these plants thrive only when some particular salt is present in certain percentages. Other varieties have been found to indicate larger percentages of alkali. The type of alkali-indicating plants, their condition of growth, and the area occupied by them, may therefore enable the engineer to estimate the scale on which his reclamation operations must be conducted. (For detailed particulars regarding these alkali-loving plants, the reader is referred to " Soil Alkali," by F. S. Harris.)

Various attempts have been made, particularly in India and the United States, to reclaim alkali-impregnated land. In some cases the surface of the area has been covered with a thin layer of clean river sand which has been subsequently ploughed into the soil. This has resulted in an improvement in the fertility of the areas thus treated, but the cost of such experiments has shown that the remedy, which only consists in reducing the percentage of alkali in the soil by diluting it with uncontaminated sand, is not practicable on a large scale. It

frequently happens that river sand of suitable quality is not available when desired, nor is the continued accumulation of alkali prevented, so that the effects of this treatment are not permanent.

Another method consists in adding a calculated amount of powdered gypsum to the soil with the object of effecting the following chemical reactions :

(Gypsum) Calcium suphate (Ca SO_4) + (Black Alkali) Sodium carbonate ($NaCO_3$) to give
(White alkali) Sodium sulphate (Na_2SO_4) + (concretionary limestone, Calcium carbonate ($CaCO_3$)

This procedure therefore involves the addition of large quantities of material and requires its thorough mixture with the soil. It has the distinction of being both a diluent and a chemical purifier, and has proved useful in certain areas where the physical constitution of the soil itself has been thoroughly investigated. It is, however, expensive and does not appear to answer very well in damp clayey soils which would appear to require an admixture of sand to render them more porous.

Hume states that a ton of gypsum plaster was added per *feddân* (about an acre) to five *feddâns* of absolutely sterile soil. Three of these *feddâns* which had not previously been cultivated were washed and drained after treatment and as a result yield an excellent crop of Egyptian clover (bersim). The method of washing out the sodium carbonate consists in making deep trenches round certain areas, and flooding the entrenched section so that the water percolates into the trenches and is carried away to streams. The operation, repeated two or three times, has been found very effective as a temporary remedy.

The subject of "Base Exchange," first discussed by J. T. Way (*Roy. Agric. Soc. Journ.*, Vol. II, 1850, p. 359) has recently been brought to special notice by J. A. Prescott (*Cairo Science Journ.*, Vol. X, Nos. 106 and 107, 1922, pp. 58–64). The action of base exchange is briefly that of the action of Permutite as a water-softener. This substance, obtained by fusing Kaolin, with sodium carbonate and quartz, is practically the same in composition as the natural zeolite minerals, *e.g.* stillbite, *i.e.* aluminium silicates united with an alkali or alkaline earth. It can exchange all its sodium for an equivalent amount of alkaline earth—all the calcium and magnesium salts (bicarbonates and sulphates) in the percolating water are absorbed by the permutite, while the sodium goes into solution in the form of sodium bicarbonate. When the sodium of the permutite is exhausted, it can be regenerated by simply passing a solution of common salt through it. This changes the calcium or magnesium nature of the permutite (or zeolite) back to the sodium condition—the calcium being replaced. It would thus

appear that if an alkali soil is washed with calcium bicarbonate, the sodium can be washed out as soluble bicarbonate.

In all the above methods it is evident that the actual percentage of alkali in the soil itself is reduced, but, as the source from which this alkali is derived is not cut off, it is evident that the remedial processes must be periodically re-applied. The only effective method of reclaiming alkali-impregnated lands is to cut off the source of supply by an operation which also aims at reducing the percentage of alkali in the soil. It is clear that the alkali is derived from the saline sub-soil waters by upward capillary movement and subsequent evaporation. Consequently, if the level of the sub-soil water could be lowered by an amount which would induce any surface water to percolate into the ground, the problem would be solved; for not only would the supply of alkali be cut off, but also the alkali in the soil would be washed back to the ground water and the contaminated land be rendered fertile. The only methods of attaining such a result are (1) by an elaborate system of deep draw-off channels; or (2) by establishing pumping stations at regular distances in the area to be reclaimed, and by judicious treatment with a view to effecting a base exchange to advantage.

In alluvial tracts, where saline sub-soil water is known to be present, there are two urgent considerations with regard to the construction of irrigation canals and the removal of the surplus water from the irrigated tract. They are—that the main and distributing canals should have (1) impervious channels (*i.e.* lined canal beds in porous ground), and (2) deep, unlined, infiltration, draw-off channels from and below the area under the irrigation command of the canal system. The idea, in the two cases, being to prevent the saline ground water-level rising too close to the surface of the ground in the adjacent tracts, and, by capillary action and evaporation, impregnating the soil with various salts which are harmful to plants. In marshy or water-logged areas in which the waters are brackish with injurious salts, the only method of reclamation is to drain off the surface water and lower the ground water-level by draw-off canals, or to resort to pumping. In both cases the ground water-level should be lowered sufficiently to prevent upward capillary movement. The alkali-impregnated soil, being subject to the wash of percolating rain or irrigating water, or both, will in time be leached of its harmful ingredients. Much depends on the nature and texture of the soil as to the ease or difficulty with which the alkali will be washed out.

An elaborate drainage scheme for drawing off the surplus water of an over-irrigated area by means of gravity infiltration channels, or by pumping from various centres, appears to be the only method of

obtaining a permanent solution of a problem of this nature. There is no doubt that it will be costly, particularly if the supply canals have also to be lined; but it may be stated that an extensive scheme, based on the erection of units of electrically-driven pumps placed in each square mile of a large alkaline-contaminated area, was recently put forward by experienced engineers who were familiar with the local conditions of the area.

RESERVOIR BASINS.—In most cases the site of a reservoir must be in a river valley and the river water impounded by means of a dam. It is essential, therefore, that the geological structure of the valley in question should be thoroughly explored. The subject of valleys in general has been discussed in Chapter XIV. Further particulars regarding the structure of reservoir basins will be found in Part II of this book in the article (Chapter XI) dealing with the location of dams. It is perhaps unnecessary to remind the engineer that the presence of porous rock, such as massive limestones, shattered quartzite, open-textured sandstones, decomposed granite or basalt, beds of conglomerate, etc., in the basin of a reservoir is taken by the geologist as a condemning factor. This is particularly true if the structure of the strata is such as to allow these porous rocks to constitute draw-off channels from the reservoir basin to a point of discharge at a lower level. On the other hand, the presence of a thick bed of impervious clay over the floor of the projected reservoir basin may render the site perfectly safe, no matter how porous the underlying rock—provided, of course, that the porous rock is nowhere exposed in the reservoir basin below the water-level of the impounded water.

The most attractive site from the engineer's point of view is naturally a valley constricted by a gorge at its out-fall and with steep banks up-stream. The prospect of a small dam holding up a large volume of water with a minimum extent of water spread is always attractive. In very many cases such features are indicative of excellent sites from a geological point of view, but this must not be presumed to mean that a detailed examination can be dispensed with. The higher the proposed dam, the more minute should be the preliminary investigation.

When collecting data in connection with a proposed reservoir, the engineer naturally goes far afield, usually up-stream, to obtain facts regarding the rainfall and discharge from the catchment. It is advisable for him to extend his observations laterally and down-stream. He may find that adjacent mines are likely to be affected by the leakage from a proposed reservoir, or that the presence of copious springs in the vicinity may lead to the discovery of unsuspected fissures in the bed of the reservoir basin.

FACTORS WHICH GOVERN WATER-TIGHTNESS.—Reference has already been made to the usefulness of a thick bed of impervious clay on the floor of a valley which is under examination for a reservoir site. As stated, such a deposit, if completely masking underlying porous rocks, renders the reservoir basin watertight. Cases are known where a comparatively thin bed of porous material has been found underlaid by impervious strata in such a manner as to make perfectly safe against leakage what at first was apparently a hopeless site. A series of beds, having gentle up-stream dips and consisting of a zone of bedded limestones overlaid by a thick sheet of impervious shales and these in turn covered by sandstones, can produce perfectly watertight conditions, provided the dam can be built on the shales.

A. L. Du Toit, in a paper (" Geology in Dam Construction ") read before the South African Society of Civil Engineers, 1922, gives some excellent examples of the water-tightness of reservoir basins on apparently worthless sites. He says (page 19), speaking of a site at Klerk's Kraal :

" the Black Reef quartzites are resting on the granite and dipping northward beneath the dolomite from which issue the springs forming the ' eyes ' of the Mooi River. Since the underflow from the dolomite constituting the basin is being brought up by the quartzite and granite here, an impounding reservoir is quite feasible upon this barrier."

In some cases a dike or sill of igneous rock may cross a valley obliquely, and constitute a veritable submerged dam to all water percolating through the porous strata under the floor of a reservoir site. Du Toit furnishes an example of this kind, and it is the more interesting because it is an alternative suggestion to the one at Klerk's Kraal give above. He says :

" The only other chance of storing water directly upon the dolomite is to take advantage of, and to found the wall upon, an igneous dyke crossing the valley. At Bank and again at Oberholzer Station on the Wonderfontein Loop broad syenite dykes behave in this manner, cutting up the dolomite into more or less watertight compartments, shown by the way in which the underflow is brought to the surface by each intrusion only to vanish again a little further along the hollow."

The same writer gives yet another example, but this entails a somewhat more intimate knowledge of the local geological structure. Speaking of the efficiency against leakage afforded by coverings of thick clay, Du Toit says :

" The water-tightness of some of the vley ground over the dolomite is phenomenally high, as has been proved most definitely around

certain of the Zwartkopjes pumping stations of the Rand Water Board in the Klip River Valley. Several of the twin shafts (continued downwards by bore-holes) are located not far from the margin of the broad vley, which the Klip River makes in this part of its course and tap their water in the dolomite at depths down to 200 feet beneath the valley floor, the supplies from individual stations ranging from 100,000 to 800,000 gallons per diem. The river water, and consequently that in the vley, has for long been contaminated with small quantities of calcic sulphate due to the mine dams along the Rand, yet not until the end of 1913 were more than traces of this substance found in the dolomite water that was being pumped. There has been an increase in the figures during late years, which nevertheless I have good reasons for believing is due not so much to overpumping, as to the drying up and the subsequent burning out of the vleys, leaving areas of hard black soil with gaping fissures ready for the season's floods."

Although it is true that the geological structure of the strata plays an essential part in regard to the selection of reservoir sites, it is to be remembered that the texture and conditions of the rock which is actually exposed in the valley floor are equally important factors. In addition it may be mentioned that the finest joints and bedding planes complicate the problem to an appreciable degree: the loss from even a small open fissure, especially when the reservoir is full and the hydrostatic pressure is felt, may be far more than the leakage due to percolation through a relatively porous rock.

Clays and shales are generally impervious. All very hard, fine-textured rocks, though impervious in themselves, are usually jointed. This may result in greater leakage losses than the seepage from a porous-textured, unfissured rock. Nearly all igneous rocks become porous when they are decomposed. The unaltered varieties, on the other hand, are seldom free from joints. In the fine-textured types, *e.g.* basalt, the joints are generally close together. Coarse-textured masses, like granite, have fewer but larger joints. Undecomposed, metamorphic rocks, *e.g.* banded gneisses and schists, are impervious to percolating water in a direction at right angles to their foliation; percolation may, however, take place along the planes of foliation. Buckled and folded varieties of all hard rocks are liable to contain joints, or fissures, or cleavage cracks. Massive, hard limestones are seldom without strong joints, and, being soluble in certain kinds of infiltrating water, the channels of percolation tend to become larger. If, added to this, there is the presence of the "head" of water in the reservoir, it is evident that in time the leakage will be enormous.

CATCHMENT AREAS.—The subject of rainfall catchments and run-off flow has already been touched upon in Chapter XIII. However, the term catchment may be used for the drainage system of a

river as well as for the rainfall catchment of a given reservoir, and the term can be applied to the exposed out-crop of porous rocks through which part of the rainfall percolates into the ground and joins the underground supply of some water-bearing strata. Thus it is seen that the nature of the rocks which are exposed within the limits of a drainage or catchment area influence the amount of run-off and percolation which a given rainfall will produce. If the exposed rocks are porous, the run-off proportion of the rainfall will be small, while the amount which sinks into the ground will be comparatively large. In the case of an out-crop of inter-bedded, porous, and impervious strata, percolation will only take place in the out-crops of the porous beds. The porous beds may be vertical or inclined or they may dip in any direction in the valley. The water which percolates into the out-crop of such beds in the drainage area of one river system may re-emerge as springs, and contribute to the drainage system of another river. In many cases the water will not re-emerge at all; it will percolate down, either to the standing water in the porous bed, or into the standing water of a complex underground water system. In the same way as the slope of ground and vegetation affect the run-off of a surface catchment area, so the porosity of the rocks affects the rate of percolation from a porous out-crop. The extent of the area on which rain falls and the total rate of rainfall precipitation are as important in determining the run-off flow from an impervious drainage area as they are in ascertaining the probable amount of water which will percolate into a water-bearing stratum from an out-crop of known porosity on which the rain is precipitated.

In this connection the following, taken from "An Egyptian Oasis," by H. J. Llewellyn Beadnell, 1909, p. 6, is of interest:

"the Libyan Desert is the eastern and most inhospitable portion of the Sahara . . . its area is about 850,000 square miles . . . the region is, to all intents and purposes, rainless . . . the greater portion of the Libyan Desert is quite devoid of vegetation and water-holes, and is, in consequence, uninhabited even by nomad tribes. At the same time, the extreme barrenness of the region as a whole is in great measure counterbalanced by a number of fertile oases, in which there is a permanent resident population, deriving its water supplies entirely from underground sources. . . .

"Underlying the greater part of the Libyan Desert are porous sandstones, and these, when pierced by deep borings put down from the lower-lying parts of the floors of the depressions, yield abundant supplies of water of remarkable purity. As these sandstones, as well as the shales with which they are associated, have a general dip or inclination from south to north, we are led to infer that they outcrop or come to the surface to the south, so that in all probability the water with which they are so highly charged has its origin in that

direction. Whether the water obtains access to the sandstones by direct infiltration of the rains of Abyssinia or the Sudan, from the swamps of the Sudd region of the Upper Nile, or from the Nile itself in the Nubian reaches, has not yet been decided with certainty. Recent observations, however, show that far more water is lost in some reaches of the Nile than can be accounted for by irrigation and evaporation, and it seems probable, therefore, that the excess disappears by infiltration into these sandstones." (See also "The Nile Flood and Rains of the Nile Basin, 1906," Survey Dept., Cairo, 1907; "Some Geographical Aspects of the Nile," *The Geographical Journal*, November, 1908, Vol. XXXII, No. 5.)

CHAPTER XVII

UNDERGROUND WATER SUPPLIES

GROUND WATER UNDER STREAM BEDS.—The ground water level generally appears to be nearer the surface under river beds than elsewhere in a given area. The phenomena met with in various places are suggestive of percolation from the river to the ground water. This transfer of water tends to raise the level of the ground water to that of the river. Under most rivers there is an underground flow or seepage of water immediately under, and parallel to, the river bed. This underground flow would probably be continued long after the river bed is dry. Owing to the nature of the rock surface under the sand of a large river the underground supplies may be deflected. In the view shown in Photograph XIV it was finally necessary to sink a well down to the rock and drive a tunnel under the river. A charge was place in this tunnel which was then filled with pebbles. When the charge was blown the river bed was broken and large supplies of water tapped.

In cases where sand or porous rock underlies the bed of a stream, this underground flow can often be easily detected. An example of the use of this ground water below large river beds may be of interest. The cases cited are those of Lahore in the Punjab and Karachi in Sind. (Extract from " Ways and Works in India," by G. W. Macgeorge, 1904, pp. 474 and 478 respectively.) Taking the case of Lahore first :

" The supply of water is taken from wells sunk, practically speaking, in the bed of the Ravi river, from which it is lifted by pumps into a service reservoir. . . . It is well known that the valleys through which the Punjab rivers flow afford a constant and never-failing supply of water. Below their surface run, in fact, clear sparkling underground rivers, whose flow is continuous and inexhaustible at all seasons, and it is this underground Ravi that has been laid under contribution for the water-supply of Lahore. . . . As the current of the underground river flows from east to west the wells are placed in a straight line north and south, at right angles to the stream."

Karachi water-supply, p. 478 :

" The Malir river, which rises in the mountainous district between Karachi and Sehwen, drains a sparsely populated country 600 square

miles in extent. At the point selected for the supply-wells, it is about 2,100 feet wide, and when in flood it discharges a vast body of water. For the greater part of the year, however, the bed of the river is perfectly dry, but water is everywhere to be found by digging a few feet below the surface of the sand. About 1,000 feet from the near bank of the Malir, which is well defined, two wells, each 40 feet in internal diameter, 36 feet deep and 400 feet apart, were sunk. These wells supply by gravity, through a conduit over 18 miles in length, and principally constructed of masonry, a service-reservoir situated close to the town of Karachi. . . . About three miles from the Malir, the line of conduit crosses a smaller river called the Thudda, and as the bed of this stream, at the point of crossing was at a lower level than the bottom of the wells, the excavation of the trench for the conduit was commenced at this point, and carried onwards to the site of the wells. By this means all the water found, both in the conduit-trench and the wells, was drained off into the Thudda. An enormous extra expense in pumping was saved by the possibility of this expedient, as it was found that for a period extending over many months the volume of water drained through the conduit-trench excavation amounted to two million gallons of water per day. As soon as the excavation of the conduit-trench and the two wells was completed, the latter were ' steined ' or lined with masonry 3 feet thick, consisting of large blocks of stone, laid dry; the joints being everywhere left rough and open, so as freely to admit water. Above water level the lining-wall is set in mortar, and is carried to a height of 23 feet above ground level. . . .

" In the year 1873, the question of the water-supply was again taken up, and in order to reduce its initial cost—the price of iron being still high—it was proposed, in view of the cheapness and excellence of the stone available in the neighbourhood of Karachi, to substitute a masonry conduit, built underground, in place of a cast iron main.

" The distributing or service reservoir is 200 feet long and 150 feet wide, and contains a maximum depth of 10 feet 9 inches. The total capacity is nearly two million gallons. The reservoir is built in an excavation, and is roofed over with rubble masonry, concrete, and earth, supported on lines of arch work. A partition wall runs for nearly the whole length of the reservoir, and separates the inlet-pipe from the main delivery pipe, thus ensuring a complete circulation of the water. The water-level in the reservoir is 55 feet above the average ground floor-level of the houses in the native town."

If the thick, alluvial deposits of an area are impregnated with saline matter, it is almost certain that the water from wells in this region will have a brackish taste. The washing action of the subsoil water under the river beds of such an area will generally have removed the saline matter from immediately beneath the river channel; consequently, when the river runs dry, *shallow* wells dug on the banks, or in the river bed, should furnish " sweet " water. If these wells are too far from the river or sunk too deep in the river bed, they will tap saline water.

Fig. 69 illustrates this point; it represents the cross section of a river channel, and shows the position of good and bad wells.

Such an occurrence of saline water is met with throughout an area more than 30 miles in length along the valley of the Purna river in Berar. Wells are sunk in this saline tract for the purpose of obtaining brine. Some of these wells are 120 feet deep, and tap the brine under considerable hydrostatic pressure. The valley of the Purna river in this region appears at one time to have been a lake which was produced by earth warping across the bed of the valley; the lake has been filled in by the streams which drain the surrounding lava-covered country. Presumably the sodium calcium and salts have been leached from these basaltic lava flows. There is no salt on the surface—the country is a rich cotton-growing area.

FLUCTUATIONS OF GROUND WATER LEVEL.—The experience which has been acquired in sinking wells and putting down borings shows that stationary ground water occurs almost everywhere below the surface. In some areas this ground water lies at great depths; in other places, it may be close to the surface. After a prolonged spell of dry weather, an appreciable fall in the ground water level may take place. Similarly, a continuous period of rain may result in a rise of the ground water level. These fluctuations of rise and fall may vary from a few inches in fissured rocks to over 50 feet in porous strata.

INFILTRATION CHANNELS AND WELLS.—In most countries, large quantities of water are obtained from wells—particularly in villages and outlying places. The majority of wells for domestic water supply seldom exceed a depth of 60 feet. In some districts it is necessary to sink to greater depths. Some factories obtain water from wells 200 to 300 feet deep. When the ground water is known to lie at depths greater than 200 feet, especially below hard rock, it is usual to put down borings; in rare cases these borings attain a depth of 2,000 feet.

Wells for domestic supplies are frequently found in the vicinity of stream courses, the wells evidently tapping the underground percolation which is associated with the stream flow, and which, as previously stated, must continue for a considerable period after the stream itself has run dry. In regions in which little is known regarding the underground water, it would, therefore, be better to locate wells at the junction of stream courses than anywhere else, unless local knowledge gave reasons for other sites.

ALLUVIAL DEPOSITS.—There are many factors which complicate the problems of water-supply from wells. The most important of these is the texture and geological structure of the rocks which

occur in a given locality. It is well known that the larger the diameter of a well which is sunk in porous ground below the ground water-level, the larger the amount of water which will enter the well in a given time and consequently the greater the capacity of the well. In some cases, deep trenches or infiltration channels cut in alluvial water-beairng ground have, for some periods, proved of enormous value in relieving the distress caused by water-shortage.

Deposits of gravel and sand, which are occasionally found as an apron or fringe to a range of hills, frequently contain excellent supplies of water in an otherwise waterless region. In Baluchistan this type of débris is locally called *dhaman* * ; elaborate methods and a system of shafts and tunnels known locally as karezes (*Rec. Geol Surv. India*, Vol. XXV, Part I, pp. 41–44) are employed for tapping the contained water. Low-gradient channels are cut and then continued as tunnels, sometimes for as much as a mile, into the débris. The gradient of the floor of these drivages is, of course, outward, so that when the ground water is tapped a steady flow emerges from the cutting.

H. J. Llewellyn Beadnell gives an interesting example of this kind in his book, " An Egyptian Oasis," 1909, p. 168. He says :

" Underground aqueducts," similar to the Persian kareez but made by the Romans, " are to be found to some extent in all the chief oases of the Libyan Desert, but in Northern Kharga they far exceed in magnitude anything known elsewhere. In their simplest form they consist of deep trenches connecting the wells with low-lying areas of cultivable land, the object being to tap the bores at the lowest possible levels, in order to obtain the greatest discharges. . . . When the excavation of the trenches was completed, the open portions were covered over with large flat slabs of stone, so that the channels were not only well protected from blowing sand, but quite invisible on the surface. . . . The underground conduits at Dêr el Ghennîma were indeed quite unsuspected before they were accidentally discovered a year or two ago. . . . These short tunnels, tapping the water of artesian wells bored on high ground, are quite insignificant compared with the extensive systems of subterranean aqueducts driven into the solid rock in various localities in the north of the oasis. The most remarkable of these are found at Um el Dabâdib, at Qasr Lebekha, and in the neighbourhood of Qasr Gyb . . . the present Omda of Kharga village got together a number of men and cleaned out one of the tunnels (at Um el Dabâdib) from top to bottom, with the result that, after a lapse of perhaps 1,000 years, water again flowed from the

* In the Imperial Gazetteer of India—North-West Frontier Province—the following remarks occur (p. 195) with regard to the *dhaman*, or ' skirt of the hills,' in the Dera Ismail Khan District. " It is a level plain without trees or grass, and, except when cultivated, is unbroken save by a few scattered bushes. In places even these do not grow, the soil being a firm, hard clay into which water does not readily sink, though after continuous rain it is turned into a soft, tenacious mud, and the country becomes impassable. Such is locally called *pat*." The Dhaman is the strip of country bordering the hills, while the *kachi* is the riverain tract between it and the Indus.

mouth of the aqueduct. . . . When I first visited the place in January, 1905, I found the discharge from the mouth of the aqueduct was between 30 to 35 gallons per minute. . . . On my expressing a desire to examine the underground aqueduct, Sala led the way to one of the man-holes situated a couple of kilometers to the north, near the upper end of the tunnel. . . . The shaft, which I afterwards found to have a depth of 40.3 metres (132 feet) goes down perpendicularly, and when the bottom was reached, I found myself standing in a gently flowing stream of water which I knew continued its underground course for at least 2 kilometres to the south . . . the tunnels were run under the valleys rather than beneath the intervening ridges with the express object of keeping as near the surface as possible, so as to avoid unnecessary excavation in the sinking of the vertical shafts, and to reduce the labour involved in hoisting the excavated material to the surface. The engineers (Roman) were at the same time careful to avoid the actual beds of the valleys, as there the soft nature of the ground would have necessitated a considerable amount of stone pitching, without which there would have been constant falls of the loose detritus, consisting of sand and pebbles with large blocks of limestone, forming the actual floors of the valleys . . . the longest of the tunnels is the most westerly, measuring 4.6 kilometres from the point of origin to its exit on the west side of the ruined fort (Um el Dabâdib) the four together having a total length of 14.3 kilometres. The actual length of the horizontal excavation is, however, considerably in excess of this figure, as there are very numerous subsidiary collecting branches ramifying from the main tunnels . . . the particular shaft I descended had a depth of over 40 metres, and subsequent levelling, from the exit of the aqueduct to a point above its origin, showed the most northerly one to have a depth of not less than 53½ metres (175 feet). Along this tunnel, which has a total length of 2.9 kilometres, I counted exactly 150 shafts, so that their average distance apart is between 19 and 20 metres . . . we may safely say that the construction of the four subterranean aqueducts and the 600 or 700 vertical shafts meant the excavation and removal of over 20,000 cubic metres of solid rock."

Abundant supplies of water are often to be obtained by wells or filter cribs from the sands in the apparently dry beds of large streams (see Fig. 66). In some cases, where the subsoil and underground water of an alluvial tract are impregnated with saline matter (usually chloride and sulphate of soda), shallow wells in the dry stream bed may be the only sources of " sweet " water supply in a wide tract of country. If these wells are sunk too deep, they will pass through the zone from which the salts have been leached by the underground flow of the stream, and tap saline water (Fig. 65, which represents a section across the river bed of such an area, illustrates this point). Reference has previously been made to the danger of diverting the flood flow of streams in regions where these conditions exist.

TUBE WELLS.—Before dealing with other questions of under-

ground water-supply, mention must be made of the use of tube wells in alluvial ground or in soft porous rocks. The whole subject has been very ably dealt with by A. Beeby Thompson in his book, "Emergency Water Supplies," 1924. On page 54 this author says:

"The advantage of tube wells over the sinking of shafts may be classified as follows:

(*a*) Simplicity.
(*b*) Speedy construction and withdrawal.
(*c*) Cheapness.
(*d*) Ease of dealing with incoherent ground.
(*e*) Exclusion of undesirable surface water.
(*f*) Protection from surface pollution.
(*g*) Impossibilities of tampering with water.
(*h*) Quick cleaning of water through screening.
(*i*) Protection from surface flow or flood."

He goes on to say, however, that:

"the following essential conditions must be fulfilled:

(1) Strata must not be too hard to resist the effective penetration of a pointed tube.
(2) If the water is not under a 'head' they are useless, without modification, if driven beyond 20 to 25 feet, as the water cannot be raised by a suction pump, and their dimensions do not admit of the insertion of a deep well pump.
(3) There must be beds of sand or gravel with sufficiently large voids to admit the free entry of water into the tube as fast as it is abstracted by pumping."

As regards the selection of sites, it is evident that geological knowledge is necessary, as, for example, where saline water is present; but tube wells may commonly be put down in the following situations (p. 77):

(*a*) Deltas of large rivers.
(*b*) River valleys, stream beds and ancient and modern water courses.
(*c*) Plains in which rivers meander, or lakes occur.
(*d*) Beaches or dune country.

It is almost unnecessary to say that tube wells are normally used in alluvial ground or in definite water-bearing strata, *e.g.* sandstones, chalk, laterite, etc. It is generally a waste of time and money to put such wells down in impervious rocks unless the boring also aims at securing a bore of the strata.

TOWN WELLS.—In a large number of cases, wells are sunk on high ground and are dependent on the direct percolation of the rainfall. Under these conditions, each well requires a fair-sized area of ground or catchment for its infiltrating water. While the houses are spaced at sufficient distances from each other, the wells in each

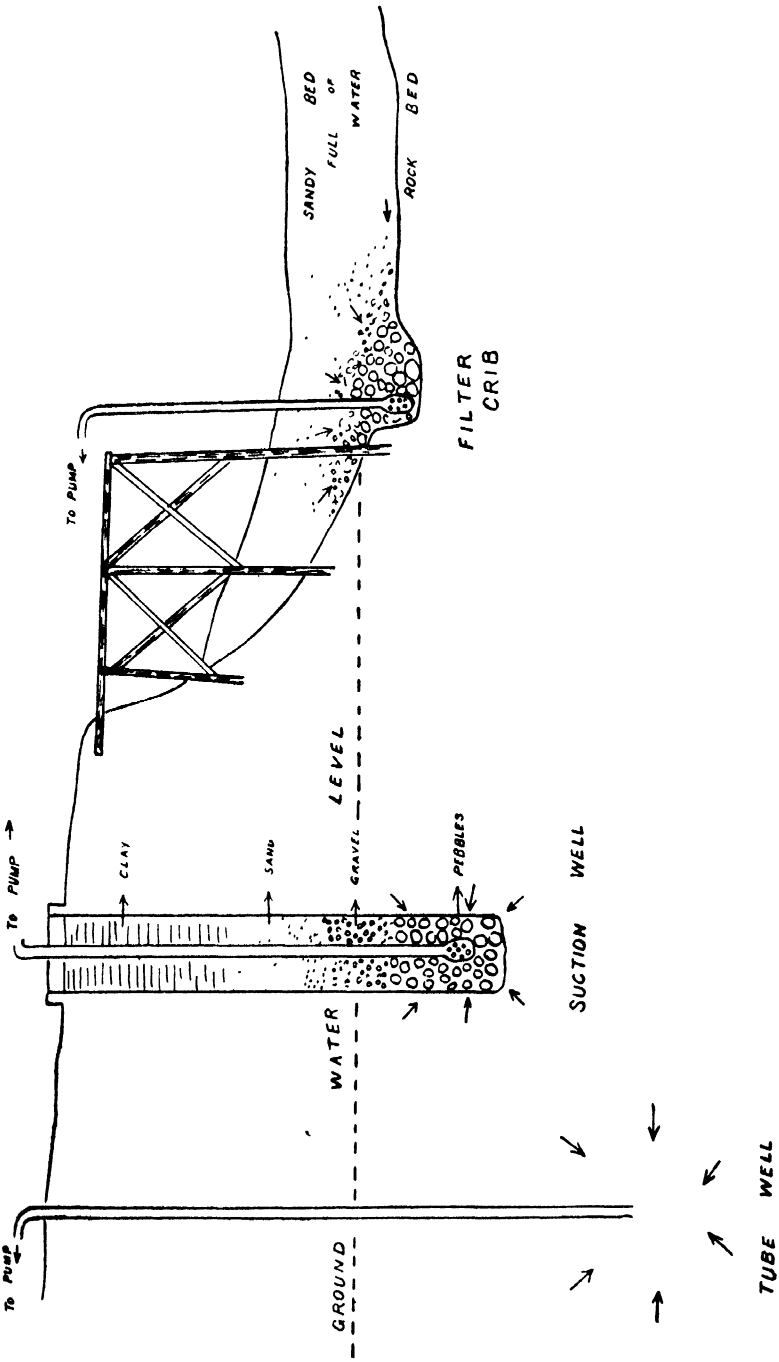


Fig. 66.
A filter cribb.

garden can usually supply the requirements of the occupants. If new houses are built between the older houses and more roads (with impervious surfaces) are constructed in the same area, it is evident that the catchment areas of the original wells may be seriously decreased. If, in addition, fresh wells are sunk within the catchment areas of the older wells, it is quite likely that the capacity of these wells will be diminished. Various expedients, such as driving short tunnels and cross drifts from the bottom of the wells or by greatly deepening the wells, may improve matters and meet the requirements of the several houses concerned. If the congestion of houses and the making of roads are continued, as will be the case in a growing town, such sources of water-supply may eventually prove unsatisfactory as well as insanitary.

INTERFERENCE BETWEEN WELLS.—An example of wells interfering with each other is given below (see "An Egyptian Oasis," by H. J. Llewellyn Beadnell, 1909, p. 144):

"Bore No. 5 is 570 metres W.S.W. of Bore No. 6, the outlet of the former being 57.38, that of the latter at 59.18, a difference of 1.8 metres. No. 5 has an internal diameter of 5 $\frac{5}{8}$ inches, 197 metres deep and 95 metres into the water sandstone; No. 6 has a diameter of 8 inches, is 146 metres deep, and 61 metres into the sandstone. The two wells had been flowing continuously for a considerable period, and during the experiment neighbouring wells were kept shut down, so that there is no reason to suppose that the observations were affected by other bores.

"Bore No. 5, discharging 114 gallons a minute, was shut down at 7 p.m. on 12th June, 1907, and re-opened at 7 a.m. on 13th June. The hourly observations, as given in the following table, show the effects produced on Bore No. 6."

Bore No. 5 closed at 7 p.m., June 12, 1907.				Bore No. 5 opened at 7 a.m., June 13, 1907.			
Time	Discharge of Bore No 6	Time	Discharge of Bore No. 6	Time	Discharge of Bore No. 6	Time	Discharge of Bore No. 6
p.m.	Galls. per minute	a m.	Galls per minute	a m.	Galls. per minute	p m.	Galls. per minute
7.0	61.2	1.0	76.6	7.0	83.7	1.0	69.0
8.15	65.6	2.3	77.4	8.0	78.4	2.0	67.7
9.0	68.4	3.0	79.2	9.0	75.0	3.0	66.8
10.0	69.6	4.0	79.7	10.0	73.0	4.0	66.2
11.0	73.2	5.0	82.1	11.0	70.8	5.0	66.6
12.0	74.7	6.0	83.1	12.0	69.6	6.0	65.3
						7.0	64.0

Per favour D. G. S. I.] SURFACE AND UNDERGROUND WATER. [Photo by Dr. C. S. Fox.

The river flow finds its way into the well at the end of the pier. The lower set of pipes were laid when the water level in that well had fallen considerably. The well in the foreground connects with infiltration galleries under the river.

THE PUMPING STATION ON THE BARAKAR RIVER.

[To face page 344.

From these figures it will be seen that the shutting down of a flowing well or the opening of a closed well may produce a most marked effect on a neighbouring well within the short space of sixty minutes, even when the intervening distance is over 500 metres.*

"The most marked example of interference with which I have met was in the case of two ancient wells at El Dêr el Ghennîma, situated only 88 metres apart, on the crest of an anticlinal fold running north and south. These wells had been sanded-up for centuries, but were taken in hand and cleaned out. The difference of level in the outlets is 2.07 metres, the high well being $34\frac{1}{2}$ metres in depth, the lower 41 metres."

	Gals. per min.		
Upper well flowed	13.2	when lower well was open (flow 50.3 gals. per min.).	
,, ,, ,,	20.5	when lower well had been closed	10 minutes.
,, ,, ,,	23.7	,, ,, ,, ,, ,,	20 ,,
,, ,, ,,	26.3	,, ,, ,, ,, ,,	30 ,,
,, ,, ,,	39.4	,, ,, ,, ,, ,,	24 hours.
,, ,, ,,	35.6	,, ,, ,, ,, open	30 seconds.
,, ,, ,,	32.5	,, ,, ,, ,, ,,	2 minutes.
,, ,, ,,	26.7	,, ,, ,, ,, ,,	7 ,,
,, ,, ,,	24.9	,, ,, ,, ,, ,,	9 ,,
,, ,, ,,	23.4	,, ,, ,, ,, ,,	$16\frac{1}{2}$,,
,, ,, ,,	19.7	,, ,, ,, ,, ,,	45 ,,

"The average velocity of water in sands does not appear to be more than 3 or 4 kilometres a year . . . the intermittent character of the flow in the case of some of the larger wells . . . is apparently due to the temporary blocking of the bore-hole by sediment. . . .

"Rapid flow through a compact sandstone is impossible owing to friction, which increases as the size of the channel decreases. . . Mr. Knibbs ('The Hydraulic Aspect of the Artesian Problem,' *Prov. Roy. Soc. New South Wales*, Vol. XXXVII, p. 30) has calculated that although in a 10 inch bore, discharging 700 gallons a minute from a 10 foot stratum, the water would have a velocity of $5\frac{1}{2}$ feet a second at the bore itself, at the distance of one mile it would only be moving through the stratum at the rate of about $\frac{1}{200}$ inch per second, or 18 inches an hour.

"A fine-grained sample of Nubian sandstone will absorb from 25 to 28 per cent. of water, a medium-grained sample 20 per cent., while a very coarse sample may take up as little as 15 per cent. The pores and transmitting capacity of the coarse-grained variety will, however, be very much greater than in the case of either of the others."

WELLS IN IGNEOUS ROCKS.—Granites and basaltic rocks constitute two of the main varieties of the igneous rocks which are met with on an extensive scale. Other types of igneous rocks occur in some places, but the remarks made with regard to granites and basalt will generally be applicable to the other types. The texture of

* See also H. J. Llewellyn Beadnell "The Mutual Interference of Artesian Wells." Geological Magazine, N.S., Decade V, vol. VI, Jan. 1909. "The Relations of the Nubian Sandstone and the Crystalline Rocks South of the Oasis of Kharga," Q.J.G.S. (London), vol. LXV, 1909.

unaltered igneous rocks is, as a rule, non-porous. The several mineral components which make up the rock are closely interlocked, consequently the prospect of obtaining water from wells sunk in these rocks would be hopeless if it were not for the joints and fissures which traverse igneous rocks. Great irregularities of the underground water-level occur in such material. In one place a well might strike a big fissure and produce enormous quantities of water; in another area, in an endeavour to increase the capacity of a moderate well, by deepening the well a strong joint may be encountered which will possibly drain the well. It is true that by going sufficiently deep these losses can be averted, but the rocks are hard and sinking costs money. Granitic rocks constitute a most difficult problem if the great joints cannot be located and if the rock is hard and compact. Decomposed granite is, however, porous, and if well sites are chosen on low ground on or near lines of surface drainage, success may attend the results of sinking a well. So much depends on local conditions, i.e. other wells in the vicinity, the configuration of the ground, etc., that it is impossible to say what should or should not be done, without detailed examination, in particular cases. Basaltic rocks, on the other hand, are more heavily jointed and, if covering large areas of country, will generally occur as beds of lava—perhaps 30 to 100 feet thick. The separate sheets of lava are normally separated by beds of impervious clay; in rare cases porous strata may be intercalated. The water in the basalt layers will invariably lie or percolate along the numerous joints which traverse these rocks. The upper part of each lava stratum is generally decomposed and porous, and should therefore contain most water. In these rocks, if insufficient water has been encountered, it is wise to continue sinking and terminate the wells in the upper part of an underlying lava flow. Coarse-textured basalts, or dolorites, are sometimes met with, and in these the conditions become more like those of granite areas. In the majority of cases, except for granite and sheets of basaltic lava, igneous rocks do not occupy large surface areas. They rather constitute zones or belts in sedimentary or metamorphic rocks.

WELLS IN SEDIMENTARY ROCKS.—The most familiar types of sedimentary rocks are various kinds of sandstones, shales, and limestones. Coarse, open-textured sandstones are usually good storage reservoirs for underground water—provided the topographical and structural conditions are suitable. Wells in shales are usually failures; very rarely some hard slatey shales are fissured sufficiently for the percolation of water through them. Thinly bedded limestones are also very unreliable sources for water. In the case of massive limestones, if the structural and topographical conditions are

suitable, great subterranean channels and pockets full of water may sometimes be met with. Cavities of this kind are caused by the solvent action of the percolating water in its passage through fissures in the limestone. These sources of supply are subject to sudden cessation, particularly after earthquakes, owing to the softness of the rock and the collapse of these subterranean caverns and channels.

Sandstones are perhaps the most important of the sedimentary beds in questions of water-supply; they, however, vary in texture and porosity. Coarse, soft-textured types allow of easy percolation and hold large quantities of water in the interstitial spaces between the mineral grains. Fine-grained varieties do not permit so free a percolation as the coarse types of sandstone. In many sandstones the pore spaces have become choked with precipitated lime or iron oxide of silica, and the rock has been rendered impervious.

The regularity of the bedded structure of sedimentary rocks, especially when the strata have been folded or tilted to occupy inclined positions, is sometimes not appreciated. Instances have occurred in which wells have been abandoned within a few feet of success when the depth could have been calculated. The out-crop of a certain porous horizon often shows the dip of the bed very clearly, and with this information the depth of the well can be calculated. If care has been exercised in determining the correct dip, the completed well is frequently successful in tapping the water-bearing zone at or very near the calculated depth.

The following interesting notes on the water-supply from wells sunk in recent coral-rock in parts of the Andaman and Nicobar Islands were taken from a report submitted by my colleague, Mr. E. R. Gee:

"*Little Andaman Is.*—A landing was next made at the south-western corner of Hut Bay. Going inland for a short distance, beds of recent coral-rock were seen to comprise this portion of the coast. The inhabitants, whom we again encountered, though supposed to be allied to the hostile Jarawa tribes of South Andaman Island, and of North Sentinel Island, were quite amicable, and an enquiry for drinking-water resulted in a very interesting incident concerning the supplies of fresh water of this part of the coast. Instead of taking us to the stream of apparently fresh water nearby, we were led into the jungle to a spot about 60 yards from the coast. Folding a large leaf to form a conical cup, one of the fellows knelt down and from a small hole in the ground, amidst the dense undergrowth, produced a cup of quite clear fresh water, at a depth of about 1½ feet below the surface. The rock was here also composed of recent coral. This fresh water, forming a part of the drainage of the interior, percolating through the very porous raised coral-rock, was apparently held up by the denser sea water of the coast. The level of the fresh water so

far as one could judge, was almost the same as, perhaps a little above, the surface of the water in the bay. It was somewhat surprising that this water, occurring so near the coast, and in rocks in which the conditions for transfusion appeared to be very favourable, should remain uncontaminated even during this comparatively dry season of the year. The visit was paid during the month of February (1924).

" *Kar Nicobar Island.*—The eastern portion of Kar Nicobar Island also consists of a rim of recent coral-rock which rests on the Nicobar clays of the central and western portions of the island. A visit was paid to the village of Mus, the water-supply of which place is worth recording. Much liquor is obtained from the coconut which flourishes on the coral-rock, but wells of drinking-water occur in and around the village. These wells were all sunk in the coral-rock, often at quite short distances from the sea-shore, and the supply of uncontaminated water continued without a break. Further inquiries from Mr. E. Hart, the only British representative living in the islands at that time, resulted in the following written statement: ' Our water-supply is fairly abundant. Our deepest well is 27 feet and has 7 feet of water, quite fresh (not salt). My own well is 15 feet deep and has 3 to 4 feet of water. At high tide it has more as the water rides on the tide, but it is quite fresh. Other wells are 3 to 6 feet deep. All are dug in coral-rock and give excellent water. Some are only 50 yards from the sea, and others well inland. We have no pumps and all the wells are open; rough stones are built to keep the sand, etc., from blowing in, or logs are laid for the same purpose.'

" Evidently the water, draining over the clays of the interior, passes into the porous coral-rock. The flow towards the sea being gradual, sufficient time is not allowed for the sea-water to penetrate inland even at high tide to cause the contamination of the well-waters, although at such short distances from the sea-shore. The only result is to cause a rise in the water-level near the coast, as the tide increases.

WELLS IN METAMORPHIC ROCKS.—Gneisses and schists are typical examples of metamorphic rocks. Other varieties are schistose slates or phyllites, quartzites, and crystalline limestones or marbles. The predominant features of these rocks are their general impervious texture, banded occurrence, and generally twisted and buckled structure. Unless severely fractured and jointed, they are generally poor sources from which to obtain well water. Some percolation may take place along the foliation planes if the rocks are somewhat weathered or decomposed. The less metamorphosed types, *i.e.* the quartzites, slates and marbles, are usually jointed, and therefore may contain water in the joint planes. The question of obtaining water in massive quartzites, traversed by strong joints, is somewhat similar to that of obtaining water in granite country. The case of crystalline limestone is also similar to that of granite, although there will be more likelihood of obtaining water from the marble than from the massive quartzites.

The metamorphic rocks by their texture resemble the igneous rocks, and in their banded structure resemble sedimentary rocks; consequently, they suffer from the water difficulties of both. The gneisses and schists are particularly discouraging. The rate of infiltration even from weathered gneisses is generally slow. Wells in these rocks, if heavily drawn upon, take a considerable time to refill. Although tunnels are sometimes driven across the banding of these rocks from the bottom of such wells, their capacity is seldom largely increased.

SPRINGS AND WATER SEEPAGES.—It is proverbial that little water is to be expected either at the surface, or at shallow depths, in plateau regions where thick masses of limestones are widely exposed. This is due to the fact that practically all the rainfall sinks into the rock through countless fissures and cracks, or down "swallow holes" in depressions known as "cauldron valleys" (kesseltäler). The *grotto* and *dolinas* of the Karst or Carso country along the north of the Adriatic are well known to tourists. Such areas, desolate and waterless as a whole, are excellent *catchments* for underground water and for springs. However, much depends on the configuration of the surrounding country and on the geological structure and nature of the strata involved. Normally, the infiltrating water will continue its downward course until it reaches the stationary ground water or is diverted, at a lower level than its intake, to the surface, and emerges as spring or seepage water. The Puika river which disappears into the Adelsberg cave near Posthumia in Italy never again re-emerges at the surface. In the case of the Timavo river in the same region, east of Trieste, which disappears into the Grotto of St. Canziano it has been established that the discharge is into the sea in the Gulf of Panzano, north-west of Trieste. The river therefore has travelled more than 20 miles underground along the strike of the cretaceous limestones of Gorizia. There are, of course, numerous other examples in other countries. Mark Twain describes one in the "Adventures of Tom Sawyer," and those in New South Wales are also widely known.

Speaking of the plateau limestones (Devonian) of the Northern Shan States, T. D. La Touche (*Memoirs Geol. Surv. India*, Vol. XXXIX, Part II, 1913) says:

"One phenomenon, however, this region possesses in common with all limestone plateaux. This consists in the occurrence, often over large areas, of depressions in the surface, the drainage in which passes underground" (p. 23). Further, p. 194: "Ever since it (the limestone) was formed, or at any rate since it was raised above the level of the sea, it has been exposed to the dissolving action of water containing carbonic acid in solution . . . the removal of this matter in solution results in a general settling down of the whole mass, more

accentuated in those places where fissures allow a ready passage to the surface waters; and there is perhaps no more striking feature in the scenery of the Shan plateau than the enormous number of cup-shaped depressions due to this cause, varying in width from mere 'sink holes' of a few yards in diameter to broad valleys, several miles in length, which may be found in most places, but chiefly along the crests of fault scarps or near the edges of the deep canyons in which the larger rivers flow."

An interesting example showing how a massive limestone affects questions of water-supply is given by C. L. Greisbach in his "Geology of the Takht-i-Suleman" (see *Rec. Geol. Surv. India*, Vol. XVII, Part IV, pp. 175–190).

"The massif of the Takht itself may be described as a high tableland, roughly 8,000 feet above sea-level, which consists of a central plain of Maidan, bounded on its east and west by high ridges or rims. The western ridge carries the highest peak (Kaisergarh, 11,300 feet), and the eastern rim culminates in the celebrated Takht-i-Suleman (11,070 feet). This tableland with its two parallel rims is capped by beds of Upper Cretaceous limestone, nearly 5,000 feet thick, which dip eastward at about 20°. As might be expected water is only found on the plateau in the deep ravines and then only in the rainy season. The only water obtainable during the winter months by the Holdich Survey Expedition of 1883, was derived from snow lying in sheltered places of the Maidan and on the higher slopes of the Kaisergarh.

"The bed of earthy shales is of considerable economic importance, as on it apparently collects all the water found in the Takht range during the dry season, the superimposed limestone permitting all the moisture to percolate through its joints and fissures. The bed also marks a decided change in the rock formations. The streams which supplied our camp with water at the Pazai Kotal and the springs above the village of Niaz Kote all issue from this horizon."

Before dismissing the subject of springs, attention may be called to certain instances in which the evidence points to an upward discharge of the water from springs. The most obvious cases that come to mind are, of course, thermal springs. In these it is generally assumed that the heat of the percolating water increases in direct ratio to its depth from the surface; then, perhaps after a considerable time, the heated waters re-emerge by a different channel.

The Rev. S. M. Zwemer, in "Arabia, the Cradle of Islam," 1900, p. 21, says:

"Arabia has no rivers and none of its mountain streams (some of which are perennial) reach the sea-coast. At least they do not arrive there by the *overland* route, for it is a well established fact that the many fresh water springs found in the Bahrein archipelago have their origin in the uplands of Arabia. At Muscat, too, water is always flowing toward the sea in abundance at the depth of 10 to 30 feet below the wady-bed; this supplies excellent water. The entire region

of Hasa also is full of underground water-courses and perennial springs."

SPRINGS IN THE SEA.—G. E. Pilgrim (*Memoirs Geol. Surv. India*, Vol. XXXIV, Part IV, 1908, p. 124), speaking of the islands in the Persian Gulf along the Arabian coast says :

" One other point deserves to be mentioned with regard to the Bahrain islands (lat. 26° N, long. 50° 40′ E.) ; this is the prevalence of artesian fresh-water springs to which the northern portion of the island owes its fertility. . . . Many wells have been dug in the town of Manama itself, of which some provide brackish water and a few sweet water. . . . Springs exist in the islands of Sitra and Nabbi Salih, and in other places also.

" It is quite usual for springs to arise from beneath the sea. Of these many are situated on reefs which are exposed at low water, and from several of these the inhabitants of Moharraq obtain their drinking water. Cater (*Jour. Bombay Br. Roy. As. Soc.*, Vol. IV, p. 21-96. *Jour. As. Soc. Bengal*, Vol. XXVIII, pp. 551–627) relates how H.M.S. *Mahi* supplied herself with 700 gallons of good sweet water from a spring beneath the sea some 10 miles north-west of Manama, by putting down a hose pipe.

" It is certain that these great supplies of water are of artesian origin and are derived from the elevated country in the interior of Arabia and the highlands of Nejd where it is likely that the rainfall is fairly large. This view is supported by the information supplied by Zwemer (see *Geog. Jour.*, Vol. XIX, pp. 54–64) and others that on the adjoining mainland of Arabia, in Al Katif and Hasa, warm fresh-water springs of a similar character to those in Bahrain are very abundant."

In this connection it may prove valuable to those in search of artesian water to mention the occurrence of springs (*chinnas*) and grassy damp spots (*chamans*) in the Quetta plain of Baluchistan. Sometimes there are patches of marshy ground from which water may trickle. One such was noted by R. D. Oldham (see *Rec. Geol. Surv. India*, Vol. XXV, Part I, p. 44) two miles from Quetta on the road to Sariab.

" The great bulk of this water . . . issues from a pool . . . with a level bottom about 2 feet from the surface : this bottom is not solid but a very mobile quicksand, kept in constant motion by the action of a stream of water which is constantly forcing its way upwards from below. In 1888, a plummet was sunk into this by Mr. N. Duncan, the Executive Engineer, North Western Railway, to a depth of 100 feet before it was stopped, most probably by the friction of the sand on the sounding line."

From this it is evident that the water comes from a considerable depth and must be under a powerful hydrostatic head to reach the surface.

There is a curious feature about these seepages. They are different

to those quicksands found in low-lying ground. The rim of the pool is above the level of the surrounding surface. In some cases the size of these "craterlet-looking seepages are 60 feet in diameter with a surrounding ridge 4 to 5 feet high. Occasionally these "craterlets" are quite dry, as though the channel for the emerging water had been choked up or the pressure of the water had somehow been reduced.

When it is remembered that a large fraction of the water-supply of Quetta is obtained by boring into the alluvium of the plain, and that the water thus tapped emerges with force (it is under a hydrostatic head and thus is an artesian supply), it would seem that the occurrence of such seepages as have been described above indicate the probability of artesian water below. However, R. D. Oldham thinks that the peculiar craterlet seepages mark the sites of ancient borings made by an energetic people of 2,000 years ago. Mr. Oldham's ideas are very strongly supported by investigations at Karga Oasis, in Egypt. In "An Egyptian Oasis," H. J. Beadnell, 1909, p. 3, says:

"The term 'Oasis,' an ancient Egyptian word signifying a resting place, in its strict sense means a fertile spot in a desert, but in Egypt has usually been applied to a depression as a whole, each individual cultivated area being known by the name of the well from which its water is derived."

p. 50.—"The Egyptian oases are deep extensive depressions or hollows cut down nearly to the sea level through the generally horizontal rocks forming the Libyan Desert plateau and appear to owe their origin in great measure to the differential effects of subærial denudation acting on rock-masses of varying hardness and composition."

p. 51.—"We have no definite ground for considering that the erosion of these depressions can have been the work of previously existing rivers, and there is no evidence to warrant us in assuming them to have been formed by local subsidence of portions of the earth's crust."

p. 52.—"Changes of temperature, sand, and wind are indeed the chief agents of erosion and transportation]at the present day, and, given a sufficiency of time and a continuance of favourable conditions, we can confidently admit the combination to be capable of effecting a vast amount of earth sculpture. But the formation, in this way, of huge hollows 300 to 400 metres deep, and the removal of material amounting to hundreds of cubic kilometres, would necessitate the assumption that the present rigorous desert conditions have obtained for a very considerable period . . . we do not feel justified in assuming this to have been the case. . . ."

p. 53.—"there are good reasons for believing that tectonic movements have played an important part in deciding the general shape of the oases-depressions."

p. 110.—"It came to me as a very great surprise to find indubitable evidence that the greater part of the floor of the depression (Kharga) had at one time or another been the site of an immense take."

p. 120.—" There is good reason to believe that the depression was inhabited previous to the formation of the lake. . . .

" Is it possible, therefore, that, as the result of the industry of the ancient well borers following their initial discovery of these deep-seated sources—the long confined waters well up with irresistible force, and gradually flooded the country ? At the present day, when the pressure throughout the artesian basin must be very much less than formerly, it is not uncommon for new bores to get out of control and flood considerable areas of country."

p. 121.—" There is another explanation. . . . The very existence of artesian water depends on the presence of porous strata overlain by impermeable beds. If one or other of the porous beds, charged with water under pressure, should, through the action of denudation on the overlying beds, become exposed at the surface, the waters would escape through natural springs in very large quantities."

The problem of discovering supplies of fresh water on beaches, bars, etc., along marine shores has been discussed by J. S. Brown in "The Relation of Sea Water to Ground Water along Coasts" (*American Journal of Science*, Vol. IV, 1922, p. 274). He discusses the water-supply from wells in certain American coast areas, and mentions the occurrence of artesian fresh water along the beach at New Haven Harbour (Connecticut). He lays considerable stress on the Herzberg Law regarding the balance of a column of salt water (H) against a higher column of fresh water (h) due to the greater density (d) of the sea water. The formula being $h = H.d$. In this connection he mentions the work of Herzberg in the East Frisian Islands, of Badon Ghyben in Holland, and of Pennink in Belgium. Pennink is stated to have proved conclusively that saline water is found at a comparatively shallow depth under a zone of fresh water in the *polder* (the diked, drained, and reclaimed) tracts of Belgium and Holland.

Brown's work, however, shows that much depends on the distance from the sea, the topography of the land surface, the alluvial or consolidated nature of the strata, the occurrence of fissures in hard rocks, the season of the year, the amount of rise and fall of the tides, etc. As a rule wells sunk in tidal marshes tap brackish ground water. Bars or spits, which may be swept by waves, almost invariably contain saline water if there is a considerable rise and fall of the tides and the land surface is low and narrow. The conditions on islands are similar to those on the mainland. Raised beaches frequently contain salt water unless there is high ground inshore from which an outward percolation can take place.

In the case of the " drowned coast " of New Haven, the following interesting facts, concerning the contamination of shallow wells by sea water, were collected :

* See also " Kharga Oasis : its Topography and Geology." Dr. John Ball, Survey Department, Cairo, 1900.

Limits of zone in feet from high-tide shore line	No. of wells in zone	No. of wells contaminated in different degrees			Total No. of contaminated wells	Percentage of contaminated wells
		High	Moderate	Trace		
0—25	13	4	2	3	9	69
26—50	17	1	2	5	8	47
51—100	35	2	6	6	14	40
101—200	23	1	4	2	7	30
201—500	31	0	0	1	1	3

The three degrees of contamination are as follows: "Trace," with from 25 to 100 parts per million of chloride; "Medium," 100 to 300 parts per million of chloride; "High," over 300 parts per million of chloride. It is just possible to taste salt in water with 300 parts per million of chloride. Most of the wells are less than 30 feet deep and nearly half of them penetrate stratified "drift." The safe ratio is placed at 1 to 1, that is, a well 100 feet from the high tide shore should not be more than 100 feet deep.

Geologists interested in petroleum who may chance to read the above will probably see a similarity between these water seepages and some seepages of oil. There is indeed a common factor in all such cases, whether the fluid thus quietly extruded is oil or water or hot liquid mud or molten lava, and this is the pressure exerted on the liquid which forces it upward. Why one particular escape channel and point of emergence developes in preference to another is seldom clear. In each instance the upward pressure appears just strong enough to cause the liquid to well-up and overflow, either continuously, intermittently, or at long intervals. If the pressure were much greater, oil-gushers, geysers, and eruptive volcanoes, respectively, would result. However, this aspect of the subject carries us to the domain of three other great branches of engineering geology—(*a*) Finding Oil; (*b*) Artesian Water; (*c*) Volcanoes. These are dealt with on pages 358, 355, and 153, respectively, in this book.

ARTESIAN CONDITIONS.—There is perhaps no simpler geological structure, nor one so seldom understood by the ordinary layman, than that designated by the word artesian. It conjures up pictures of spouting fountains and flooded ditches and a cessation of water troubles.

When a porous bed of rock occurs inter-stratified between two impervious layers of rock, and all three beds are folded to the shape of a basin or a trough, the structural conditions are suitable for an artesian well (see Fig. 67). If the porous bed is thick and exposed in a wide out-crop (a large catchment area), it may contain large quantities

of water—particularly if the size of the trough or basin is large. The question as to whether the water will flow out of a bore-hole, which is put down to the porous bed in the deepest portion of its sag, is one which depends on the relative heights, or levels, of the out-crop of the porous beds and the ground surface at the top of the bore-holes

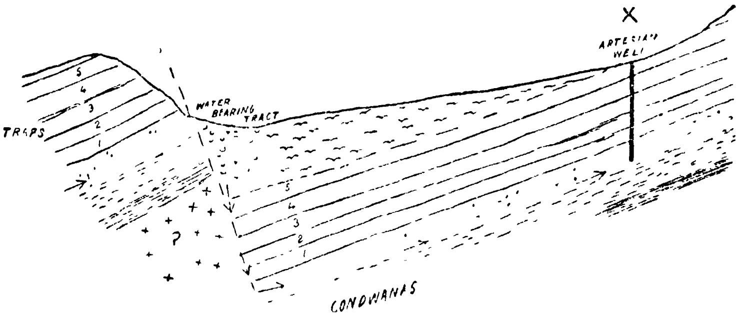


FIG 67.
Artesian conditions in fault valley.

(see Fig. 68). If the out-crop or catchment area of the porous bed is at a higher level than the top of the bore-hole, water may flow from the bore-hole when the porous stratum is tapped. On the other hand, if the top of the bore-hole is at a higher level than the out-crop of the porous bed, it is obvious that the water, although it may rise to a considerable height in the bore-hole, cannot exceed the level of its intake, *i.e.* the lowest point of the out-crop of the porous bed. In this case the water will have to be pumped out of the well; in the

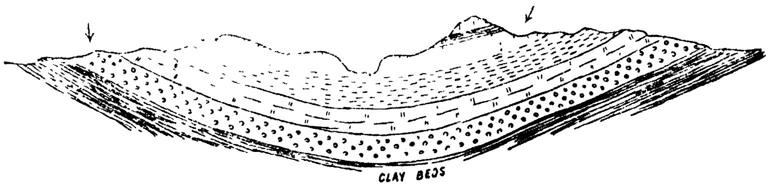


FIG 68.
Normal artesian conditions (section).

former case the boring produced a flowing well. In both cases artesian conditions exist.

There are numerous examples in which imprisoned waters are found under hydrostatic pressure. These artesian conditions show (1) the presence of channels for the infiltrating water; (2) the intercalation of these channels between impervious layers of rock; (3) a difference of level between the place where the water enters the channels and the point at which the imprisoned water is tapped by a boring. These conditions are shown in Fig. 69. In this example, when the water-bearing stratum is full of water, any additional infiltration will

cause springs to occur at C. In the case represented by Fig. 67, the fault plane functions as a channel for percolation in conjunction with the porous bed. The bore-hole completes the U-tube structure. Consequently the water will rise in the bore-hole as far as the hydrostatic pressure permits. The quantity of water will depend on the capacity of the well. If large volumes of water are available in the inter-spaces of the sandstone, and there is little "loss of head" (due to resistance to the flow of water through the sandstone), considerable quantities may be obtained from the well. If the well is of the flowing type, the first discharge of water may be more than will be subsequently maintained. When the well finally adjusts itself, so that the out-flow from the well is governed by the percolation to the well, the rate of flow may not be sufficient for the requirements of the day. In such

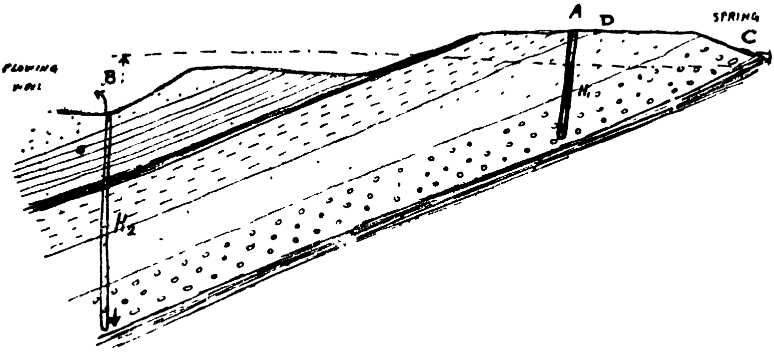


FIG 69
Flowing and non-flowing wells

cases a pump is attached, and the well over-pumped in the day and allowed to recover during the night—the total quantity being the same in each case. It is generally advisable to pump rather than to store the slow discharge. By pumping, a certain amount of suction is produced, and the infiltrating channel may be improved; in fact, the action of the tube well is introduced (see Fig. 66). In some cases two parallel faults, which let down a strip of country into a trough—*e.g.* the Great Rift Valley which traverses Nyassaland—may produce excellent artesian conditions. The faults, in such cases, may act as infiltration channels to an underlying bed of porous rock. In other instances, particularly in the so-called (granitic) crystalline rocks, the strong joint planes may function as the channels for infiltration, and, in some places, very large supplies of water, under pressure, may occasionally be obtained. A boring may tap a large cavern in an underlying limestone and, if this cavity is full of water under pressure, thereby obtain enormous quantities of water under artesian conditions. In such examples as have been given, and in various others, it is clear

that the geological structure of the underlying rocks must be correctly determined; and, equally important, the presence of an interbedded porous bed or other water-holding zone, be ascertained. The porous bed is the crux of the whole question; without it there can be no water, however perfect the structural features of the strata.

The total volume of pore-spaces in a rock is a guide to the porosity of the rock, but does not give its water-bearing capacity in actual practice. For example, the percentage of the pore-space volume of various rocks may be, roughly, as follows:

	Per cent.
Soil and loam	50
Clay (ordinary dry)	40 to 50
Chalk (soft)	40 to 50
Sand (firm)	30
Sandstone (soft)	20
Sandstone (hard)	10
Slate and shale	3 to 5
Limestone and marble	2 to 4
Granite (unaltered)	up to 1
Quartzite (fine, hard)	below 0.5

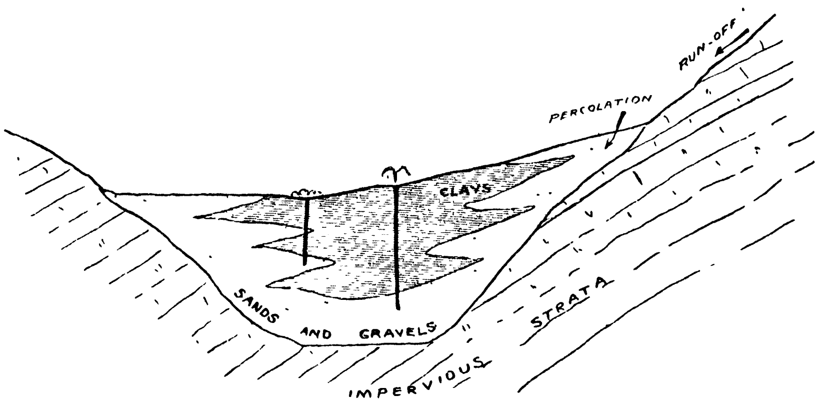


FIG. 70.
Artesian water in Quetta Valley.

Figures of this description are generally only useful for guidance in the choice of building stones, which are used in comparatively small-sized blocks; they are, however, quite useless in questions of water-supply. The pore-spaces of clays are too small and do not allow of the *passage* of water. The granites may be practically non-porous, but they are always traversed by joints, and it is from these that the underground water, in a granite country, is obtained.

Artesian water may frequently be obtained by boring in the alluvium which skirts a range of hills or fills an old lake basin. The probable structure which gives rise to this hydrostatic head of water is represented in the accompanying sketch, Fig. 70.

Quetta, in Baluchistan, obtains its water-supply from alluvial ground which is said to have the above structure. The well at the railway station passed through 120 feet of *loess*, 20 feet of gravel, and entered a quicksand. The water in this well had a hydrostatic head of 50 feet and discharged 20,000 gallons an hour.

Fresh water is often found along sandy coasts, particularly where dunes are present, at a height appreciably above the level of the sea. This hydrostatic head has been ascribed to the difference of density of fresh water and sea water. Mr. A. Beeby Thompson estimates that "a well 1,000 feet deep, sunk at sea-level, might have an artesian head of 15 feet due to differences of density."

It is difficult to imagine that such a result will take place, unless the fresh water itself comes from a source considerably above the level of the sea. There could be no better situation for such a phenomenon to be observed than that of the low-lying alluvial peninsula, barely 10 feet above sea level, which connects Gibraltar with Spain. Fresh water, for the fortress, is obtained from *wells* in this locality, but the supply is a little too brackish for use as drinking water, and is only utilized for sanitary purposes.

Among peculiarities of hydrostatic pressure may be mentioned those springs which suddenly discharge copiously when prolonged rain falls on porous strata after a dry spell. In this case it is thought that the simple process of percolation is augmented to some extent by too rapid absorption by the parched porous material of the subsoil. The result is that, as the water is thus rapidly taken up, a certain degree of expansion will occur, which must produce an expelling force on this interstitial water. The level of the underground water will rise in consequence and, if the expansion is great, springs of considerable size may make their appearance. Perhaps the best example of this type of intermittent phenomena is the *bourne* at Croydon.

OIL FINDING.—During recent years many mining geologists of limited experience have been known to base their opinions regarding an oil proposition on the presence or absence of a structure which is the exact opposite of that desirable for artesian water. In many cases this anticlinal or arch structure is perfectly correct for a favourable occurrence of oil in petroleum-bearing strata; this is due to the fact that the oil occurs with water, as in the Burma oilfields and in most of those of India. In consequence of the oil being lighter than water, it naturally accumulates in the arch of an anticlinal fold, and may be subject to an enormous pressure in just the same way as the air, trapped in a submerged bell jar, is compressed by the upward thrust of the water below. If a boring pierce the porous strata, there is naturally a rush of gas and oil to the surface.

In many cases the rocks in the arch of the fold are fractured, and there is an escape of gas and oil into the overlying strata. If this leakage reach the surface, there may be a seepage or a gusher depending on the pressure lost by the oil in traversing the intervening beds. If these beds contain water, the buoyancy of the oil helps it to the top of the water level in the rocks above the point of escape from the oil-bearing horizon.

Now, it may happen that there is no water in or above the oil-bearing beds. In such instances the same arguments hold good as in the consideration of water alone. The synclinal or artesian structure here becomes important, for the oil naturally gravitates to the deepest portion of the trough and is there subject to the greatest pressure. A boring put down to the trough of the folded strata will thus be likely to tap the most favourable part of the oil-bearing horizon. It is the synclinal structure which is the key to most of the South American oilfields.

The remarks in the above paragraph will need modification if the beds involved are somewhat tightly folded in synclinals. In such cases the pressure would force the oil outward and upward into anticlinal flexures where the squeeze is naturally less and the strata possibly broken. It would thus happen that the normal mode of oil occurrence would be found.

CHAPTER XVIII

QUALITY OF WATER

GENERAL REMARKS.—Occasions have arisen when an engineer has found himself confronted with the problem of deciding whether the water of a given locality is suitable for certain purposes. It may be a question of choosing water for drinking and domestic use; or to say if the water will be safe to use in boilers for steam raising; or possibly it is a matter concerning important building operations; or whether it is likely to prove unhealthy for sanitary purposes such as street-watering, etc.

He knows that rain-water is usually the purest form of natural water, but he is also familiar with the fact that rain-water normally contains appreciable amounts of carbon dioxide; after thunderstorms rain-water may contain small percentages of nitric acid. Again, in industrial areas, the rain-water may contain sulphuric acid or other objectionable impurities. However, by collecting the run-off rain from clean surfaces in clean tanks, as is done at Gibraltar, perfectly reliable supplies of water for domestic purposes can be obtained.

There are limits to the amount of rain-water which can be collected economically by the above methods. The rainfall may be precarious or the catchments too small for the purpose in view. In exceptional cases (Aden, 1914–18) recourse is had to the expedient of distilling sea water; this entails the use of multiple evaporators, a boiler, and condensing plant. The method is costly both in initial outlay and cost of working. Normal plants give from 1 to 2 gallons of condensed water per lb. of coal used; modern equipments sometimes produce 3½ gallons (35 lbs.) of distilled water per lb. of coal.

These are exceptional examples necessitated by exceptional cases; commonly, attention is directed to using the water of rivers and lakes, or resorting to the process of sinking wells and boring for water. In these cases the question of quality may be complicated in various ways; once the rain-water falls to the ground, geological and geographical considerations have to be taken into account.

F. Dixey ("A Practical Handbook of Water-Supply," 1931) has discussed the question of water very fully. He states that sea water

contains 3.5 per cent. of salts, or roughly 3,500 parts per hundred thousand. When a water averages 50 to 200 parts of solids per 100,000 of water, the solid content of the water is HIGH; with 15 to 50 parts per 100,000 the solid contents of the water are MODERATE; while with under 15 parts of solid matter a water is considered LOW in solid matter. Similarly if a water contains 50 to 100 parts of $CaCO_3$ (calcium carbonate) in solution it is a SOFT water; with 100 to 200 parts of $CaCO_3$ it is a MEDIUM (hard) water; and with 200 to 300 parts of $CaCO_3$ it is a HARD water. However, these mineral substances do not render a water impure. The chief impurities are those of *vegetable* and *animal* ORGANIC matter. The latter is always dangerous. Water with an unpleasant *taste* or disagreeable *odour* is always suspect. Although rarely utilised admixture of a clean clay in a suspected water may render the water, after settlement of the suspended matter, safe to use. Alum, 2 to 6 grains per gallon; a few drops of tincture of iodine or Condy's fluid, etc., are the normal means of safeguarding water intended for immediate use.

According to A. C. Houston ("Studies in Water-Supply," 1913) 40 parts of salt in 100,000 of water cannot be tasted; 50 parts of salt renders water brackish; 100 to 250 can be tasted, but the water can be drunk; 250 to 500 parts renders the water salt enough to make unbearable for continual use; over 400 parts of salt makes a water undrinkable by man.

As regards the limits permitted in the case of organic contamination Dixey gives the following:

Free ammonia	0.012	per 100,000 parts
Albuminoid ammonia	0.028	" " "
Nitrites	0.0003	" " "
Nitrates	0.389	" " "
Oxygen absorbed	0.700	" " "

Free ammonia with albuminoid ammonia usually indicates vegetable contamination, but albuminoid ammonia with chlorine generally shows contamination by sewage and is a warning of dangerous water. Acidity in water is usually accepted as a sign of bad waters, while nearly all good waters are definitely alkaline. An alkaline water is thus an encouraging indication.

As a result of the drought in England during the summer of 1934 attention has been given to the subject of installing tanks in each house for the collection and storage of rain water off the roof. It is, of course, fully understood that the roof and gutters are allowed to get washed before the roof water is diverted into the tank. It is interesting to quote (from H. B. Woodward's "The Geology of Water-Supply," 1910) that snow collected in December near London

(Kew) contained appreciable impurities which calculated for the London area (of 1909) represented 75 tons of dissolved matter, 100 tons of soot, 25 tons of salt, 1 ton of ammonia, 142 tons of other dust, etc. While a fog revealed 22 lbs. per acre (6 tons per square mile) of dust which consisted largely of—carbon 40 per cent., hydrocarbons 10 per cent., H_2SO_4 about 4 per cent., HCl about 1.2 per cent., ammonia 1.2 per cent., SiO_2, Fe_2O_3, etc., over 38 per cent., and 5.6 moisture in the fog. It is known that at Rothamsted (Herts) the amount of SO_3 brought down by rain is of the order of 17 to 18 lbs. per acre; the amount of nitrogen (ammoniacal and nitric acid) is nearly as much as 4 lbs. per acre; the chlorine is roughly 14 to 15 lbs. per acre (the sodium chloride up to 24 lbs. per acre). The chlorine brought down by rain in Calcutta is roughly 32 lbs. per acre; and 36 lbs. in Madras, 130 lbs. in British Guiana, and over 180 lbs. in Colombo (Ceylon).

SURFACE WATERS.—It is known that the waters of rivers and lakes vary greatly in character and composition. In the case of springs the differences are yet more astonishing. The waters of streams are affected by the rocks or strata over which they flow. J. Hanaman has given interesting analyses showing the composition of Bohemian waters as related to the rocks from which they flow. Thus:

	A	B	C	D	E
CO_3	35.94	30.49	32.14	46.85	3.301
SO_4	6.45	14.12	12.86	7.94	27.69
Cl.	10.15	6.39	7.24	1.66	2.87
Ca.	11.91	11.89	12.61	20.07	22.12
Mg.	5.02	3.58	5.08	5.76	5.29
Na.	11.20	10.57	10.85	6.22	3.43
K.	4.39	5.63	4.22	3.20	2.72
SiO_2	14.94	17.33	15.00	7.67	2.87
Fe_2O_3	–	–	–	0.63	–
	100.00	100.00	100.00	100.00	100.00
Salinity parts per million ..	48	65	74	343	603

A, average of 5 analyses from Phyllite.
B, „ „ 6 „ „ Granite.
C, „ „ 6 „ „ Mica Schist.
D, „ „ 4 „ „ Basalt.
E, „ „ 4 „ „ Cretaceous Strata.

The excellence of A, B and C waters from crystalline rocks is evident.

It is known, however, that rivers draining marshy grounds and swamps, as in the case of many South American rivers, are contaminated with vegetable matter and other objectionable organic substance. Also it has been established that the character of river-water may be changed in various ways. It may be used for irrigation or added to by tributaries draining other types of rock areas. The following analyses show the changes in composition of the Cache la Poudre river-water at different points of its course in Colorado (quoted by F. W. Clarke):

	1 above the north fork	2 in lab. at Fort Collins	3 2 miles above Greeley	4 3 miles below Greeley	5 Platte River below mouth of Cache la Poudre
CO_3	31.91	33.68	7.34	10.34	8.78
SO_4	9.07	23.36	59.99	54.33	55.28
Cl.	4.03	1.10	2.52	3.19	3.79
Ca.	14.53	22.58	12.31	15.00	13.24
Sr.	–	0.19	–	–	–
Mg.	2.93	5.53	6.65	5.00	4.69
Na.	10.80	5.12	9.84	10.09	12.02
K.	2.72	1.66	0.34	0.46	0.41
SiO_2	23.50	6.49	0.94	1.42	1.26
R_2O_3	0.51	0.29	0.07	0.17	0.53
	100.00	100.00	100.00	100.00	1.0000
Salinity parts per million	37	137	1,571	958	1,011

The first column indicates a very pure mountain water, relatively high in carbonates and rich in silica. Column 4 shows a sulphate water low in silica. The change is partly due to the fact that the water has been largely used for irrigating purposes, and the arid soil contains much soluble matter. In the case of the Mississippi, it has been found that the upper waters are low in sulphates and chlorides, but these come in lower down—the chlorides in part representing human contamination.

Another example is that given by Beeby Thompson in "Emergency Water Supplies," 1924, p. 176. The following table shows the progressive mineralization of water flowing from mountains into an arid delta. The form in which this analysis is presented should be compared with those given later in this Chapter. It is evident that "cyclic" salt is present in the soil, and the increasing percentage of chlorine, as the coast is approached, is probably due to this fact and not to human contamination.

Contents	Zaida	Lahej	Bir Ahmed	Dhebie Well	Saline Hamesh	Sheik Othman
	Parts per million.					
Total solids	730	1640	2800	2350	3460	5700
Chlorine	145	292	780	750	1530	1700
Sulphates	181	549	709	659	509	1740
Total hardness ..	242	565	325	850	1500	1710
Temporary hardness ..	132	165	140	40	130	?
Magnesium suplhate ..	46	385	339	275.8	193.5	?
Sodium sulphate ..	213	358	?	?	?	?
Magnesium chloride ..	nil	nil	700	nil	921.1	?

In the case of inland rivers, pollution of the water from towns and factories is best detected by the chlorine content; *e.g.* the Illinois river, into which pass the waters of the Chicago drainage canal, contains

	Total dissolved solids.	Chlorine	
	Parts per million	Parts per million	Percentage
at Morris	235.3	23.1	9.82
at Ottawa	269.4	21.4	7.94
at Lasalle	245.4	18.7	7.62
at Averyville	245.2	17.5	7.14
at Havana	236.3	14.8	6.27
at Kampsville	234.3	14.0	5.98
at Grafton	232.6	13.1	5.63
Mississippi at Grafton	150.1	3.1	2.06

This decrease is astonishing, but variation across the Mississippi at Alton (Illinois) is equally surprising.

100 feet from Illinois shore	194.1	7.7	3.97
¼ distance across ..	182.8	7.1	3.87
Midstream	160.6	4.4	2.74
¾ distance across ..	155.0	4.1	2.65
100 feet from Missouri shore	154.2	3.5	2.27

(Analyses by A. W. Palmer quoted by F. W. Clarke.)

In the case of lakes similar considerations are involved. Should the lake occupy an enclosed basin, the question of quality is greatly affected by the evaporation losses, the direction of the prevailing wind,

etc., in addition to the factors already mentioned when speaking of rivers. For example, the lakes of Rajputana at Sambhar contain saline water from which salt is obtained on a large scale. Investigations by Sir Thomas Holland and Dr. W. A. K. Christie show that the presence of this salt can be accounted for only by an appeal to wind-borne sources. It is so-called "cyclic salt." Although the lake in question is 400 miles from the Runn of Cutch, they found that, roughly, 3,000 tons of salt are annually deposited in the lake basin by the prevailing south-west wind. Their estimates indicate that by this means over 130,000 tons of sea salt are carried into and deposited in Rajputana each year. The subsequent rain washes this salt into the hollows and basins where it is concentrated.

It is not to be forgotten that the salt in the sea is carried by rivers, the waters of which have leached these salts from the rocks they have traversed. In fact it is interesting to record that the age of the oceans has been roughly obtained from data of this kind. Edmund Halley suggested in 1715 that the age of the earth might possibly be ascertained by determining the rate at which salt was being carried into the sea. The subject was left in abeyance until 1899 when J. Joly of Dublin, with information supplied by Sir James Murray and Dittmar, found by the simple calculation $\frac{\text{total sodium in ocean}}{\text{annual sodium in rivers}}$ that the age of the ocean was approximately 89,222,900 years. Subsequent calculations bring the figure to nearly 100 million years (see page 17).

It is to be remembered that we are discussing substances in solution in the water. In previous pages the question of carriage of material in suspension, such as gravel, sand, and silt, have been mentioned. It is surprising how much material is washed out of the rocks and carried away in solution by rivers.

F. W. Clarke (see "The Data of Geochemistry," *Bull., U.S. Geol. Survey*, No. 616, 1914, p. 58) estimates that, irrespective of silt, upwards of 2,500,000,000 tons of inorganic material is annually carried in solution by rivers and discharged into the oceans. His calculations are based on a drainage area of only 28,000,000 square miles, and an extraction factor of, roughly, 68 tons of soluble matter from each square mile. Sir James Murray estimates the catchment area of the rivers as 40,000,000 square miles. Using this figure with the above extraction factor, calculations indicate that chemical denudation must be removing the land surface at the rate of 1 foot thickness in 28,000 years. (See 4th Ed., No. 695, 1920, p. 59.)

The rate varies in different localities just as the character of the water differs in different places; thus T. Mellarde Reade estimated that over 8,000,000 tons of matter was removed in solution annually from

the surface of England and Wales. The extraction in this case is, roughly, 143 tons from each square smile. The rate of denudation is 1 foot in 13,000 years. Sir Archibald Geikie states that, roughly, 550,000 tons of matter are carried annually in solution by the Thames past Kingston. The drainage area of this river is about 6,100 square miles; the extraction factor worked out to nearly 90 tons per square mile. Estimates by engineers of the United States Army show that the flow of the St. Lawrence past Ogdensburg is nearly 250,000 cusecs, and that this water has a salinity of 134 pârts of inorganic solids in solution per million parts of the river water. Their data indicate an annual transportation of dissolved matter amounting to 28,000,000 tons from an area of, roughly, 280,000 square miles of land surface—the chemical denudation being 100 tons from each square mile.

These chemical losses are essentially due to the solvent action of rain-water—particularly rain-water charged with carbon dioxide derived from the atmosphere. It helps us to realise the extent to which chemical alteration of the underlying rocks must affect the character and composition of underground waters. To this aspect of the case we must now turn our attention.

UNDERGROUND WATER.—The moment rain-water, charged with carbon dioxide, enters the pore-spaces and fissures of the rocks, active chemical action begins. The more soluble minerals are dissolved, colloidal silica is liberated, and carbonates of lime, iron, magnesia, and the alkalies are formed. Undissolved substances are attacked and suffer hydration—feldspar is converted into kaolin, magnesium compounds, such as olivine, are converted into serpentine or talc, etc. This process of hydration is normally accompanied by an increase in bulk of the substance thus affected. Close to or at the surface an increase in volume readily takes place as there is no weight to prevent it. Deep down—and alteration does occur in places at great depths—the altered substance is under too great a pressure for sufficient expansion to occur, with the result that the decomposed rock may remain in a solid condition—ready, however, to take advantage of any release of pressure. In the processes of mining and tunnelling or even in deep cuttings, the engineer may meet with such cases. He uncovers the rock unsuspecting its altered condition. It may appear unchanged and hard, but after a short time the material rapidly falls to pieces or crumbles to powder by a kind of slaking process.

The alteration which is produced as a result of the processes of solution, oxidation, and hydration by percolating water is almost unbelievable. At times the change is so great that even a geologist hesitates to say what the product met with was derived from; for

example, it is known that certain cream-coloured clay-dikes occasionally met with in coal-mines are representative of basalt dikes which forced their way into the strata in a molten condition. Equally astonishing is it that the residual weathering product known as laterite, which is found capping certain plateaux in India, was once a basaltic lava also originally extruded in a molten flow.

The percolating water which has effected these changes passes on, carrying with them the mineral substances which they have dissolved. These meteoric or vadose waters either emerge in springs or join the sub-soil and stationary underground waters. They are tapped by wells and borings, and it would be remarkable if they did not carry mineral salts of one kind or another. In the majority of cases these waters are not particularly warm or heated; in a few instances they are boiling hot. In several cases emerging spring waters evolve gases, usually of a sulphurous odour—sulphuretted hydrogen; often they deposit precipitates—calcareous tufa or calcium carbonate, calcium or magnesium sulphate, sulphur, siliceous sinter, iron carbonate, etc., and, occasionally, salt, and perhaps radioactive substances, e.g., radium salts.

The waters commonly tapped by wells and borings do not exhibit these exceptional characteristics to such a marked degree. Nevertheless, well waters contain matter in solution and suspension—only the quantity of dissolved matter may be small.

As stated previously, much depends on the nature of the rocks in which they occur or through which they have passed. In limestone regions the waters are expected to contain carbonates of lime, and perhaps magnesia. Waters traversing basaltic rocks usually contain these same carbonates, but in addition may have sulphates in solution. Coal measure strata impart acid qualities to water due to the interaction of carbonaceous matter on sulphates, etc. In salt marls the waters may have large amounts of saline matter—sodium chloride and gypsum being common impurities. The waters met with in mineralized regions frequently deposit metallic substances; thus it is seen that, although a water may be clear and sparkling, even odourless and perhaps tasteless, it may, owing to the presence of too large a percentage of a given substance in solution prove harmful if used for drinking purposes and be unsuitable as feed-water for boilers.

Before passing on to the subject of water analyses and classes of water, perhaps mention may be made of so-called virginal or *juvenile* waters as distinct from *vadose* waters. When speaking of vadose waters we mean, strictly, waters of surface origin which have percolated through the soil and sub-soil and have formed by slow accumulation the so-called stationary water below ground. Till a few years

ago it was the general opinion that all water met with in the earth was of surface origin, *i.e.* vadose. Attention to detail has shown that in many cases springs and other underground waters have no evident connection with channels of infiltration, such as porous strata, fissures, etc.

In certain instances the available evidence points to a very deep-seated origin for emerging waters ; examples of such are the thermal springs (of Carlsbad), hot geysers (of New Zealand), and the steam given off during volcanic eruptions (Vesuvius). Scientific opinion, although frankly sceptical about juvenile waters which are supposed to be given off by the fundamental magma, has been influenced by the weight given to this aspect of the case by such men as Eduard Suess, Armand Gautier and J. W. Gregory.

Gautier considers that whereas the vadose or meteoric waters are subject to variations in composition, concentration, and rate of flow depending on local conditions such as heavy rain or drought, the juvenile waters are fairly constant in all essential particulars. He thinks (see *Compt. Rend.*, Vol. CL, 1910, p. 436) that discrimination is possible between vadose and juvenile waters—the former containing carbonates of lime or magnesia, chlorides, and sulphates ; whereas the latter are characterised by sodium bicarbonate, alkaline silicates, heavy metals, etc., as essential constituents, with chlorides or sulphates only as accessories, and practically no carbonates of the alkaline earths. He claims that there is a genetic connection between thermal springs and volcanic action, and produces evidence to the effect that when granite is heated to redness (in vacuo) water and gases, identical with volcanic gases, are given off. One cubic kilometre of granite is estimated to yield 25 to 30 million metric tons of water, which at 1,100° C. would produce 160,000,000,000 cubic metres of steam—such a temperature would be available at a depth of 25,000 to 30,000 metres. At this depth the steam would be subject to an enormous pressure ready to escape upward and join the vadose waters. It is an interesting presentation of the case ; but in view of the fact that granite may, in some cases, itself prove to be a metamorphic rock of sedimentary origin, its water contents could be easily accounted for. If, at a subsequent period, such a mass of granite were depressed, by fissuring and subsidence, to a great depth, the evolved steam could not be considered as juvenile water.

EXAMINATION OF WATER.—A complete examination of water involves a detailed investigation of its physical and chemical properties and a scrutiny of its bacteriological condition. These analyses are carried out by special experts, and it is beyond the scope of this book to go deeply into the subject. However, a few general

remarks on the physical and chemical quality of waters may not be out of place here.

Physical Aspects.—The *look* of a water is no criterion of quality. A clear sparkling water may, by containing organic matter, be dangerous for human consumption. Opalescent water usually indicates the presence of colloid material which may be harmful if used for drinking purposes. Turbid water, due to suspended matter, can often be made clear by simple filtration and rendered fit for domestic requirements. *Coloured waters* are usually only objectionable in appearance, but they may be contaminated with pathogenic germs, or peaty matter, or iron compounds, which have been liberated by bacterial action. Yellowish water may mean sewage contamination; blackish-brown waters are indicative of vegetable matter; red-brown waters are coloured by iron compounds. *Odours* of a disagreeable kind render water objectionable for domestic use; in many instances, *e.g.* sulphuretted hydrogen, the odour disappears after a time. Sometimes deodorization can be secured by agitating the water with dry clay, allowing the sediment to settle, and then decanting the water. Water from marshes and certain sulphate waters may have a very faint odour, but might be highly poisonous withal. The odour can best be tested by warming (to 65° C.) a sample of water in a covered dish and then lifting the lid suddenly. In most cases objectionable odours are due to incomplete oxidation of hydrocarbons and sulphides. These substances can frequently be rendered quite harmless by the careful addition of very small amounts of permanganate of potash or chlorogen. The *taste* may furnish valuable evidence as to the nature of a water. Good drinking water should be tasteless and fresh. Waters which taste flat are unattractive. The presence of iron compounds can often be detected by tasting. Brackish and saline waters, besides being unpalatable, may cause internal disorders and skin diseases, if used for drinking purposes.

Purity, acidity, and alkalinity are among the first determinations made by a chemist. He then proceeds to determine the nature and amount of the inorganic and organic compounds present. Acidity and salinity are, as a rule, undesirable characteristics in a water; the stronger the acidity or salinity, the more unsuitable is the untreated water for domestic consumption, or for use as feed-water for boilers. The presence of chlorine in inland water is usually an indication of sewage contamination. In this connection it may be mentioned that the presence of ammonia and nitrates leads to a suspicion of organic pollution. With regard to alkaline waters, perhaps the most popular determination is that of "hardness." *Temporary hardness* is usually due to the presence of the bicarbonates of calcium and magnesium;

it is partially removed by boiling, and completely eradicated by a judicious addition of lime. To the presence of sulphates of calcium and magnesium is ascribed the *permanent* hardness of certain waters. This hardness is best counteracted by the use of quicklime, or of barium carbonate and barium oxide. A slight degree of hardness is considered good, from a hygienic point of view, though most people appear to prefer soft waters both for drinking and for domestic purposes. Chalybeate waters are objectionable for various reasons; they are liable to precipitate iron compounds and thus clog pipes and taps, stain clothes, and cause rusting where more suitable waters would not. Certain types of bacteria, misnamed iron-bacteria, by removing organic matter in combination with the iron in a colourless water, liberate iron hydroxide in large quantities, and thus clog reservoirs, pipes, etc., with large quantities of this red, flocculent stuff.

In all cases where the dissolved matter is present in dangerous or objectionable amounts, the water must be treated: filtration, purification, and sterilisation are necessary in the most impure waters. Filtration may be sufficient if only suspended matter is present, but precipitation either by clay, or lime, or barium compounds, or with alum, chlorine or bleaching powder may be essential in the case of dissolved salts of the types enumerated. Successful oxidation of organic compounds is often effected by carefully adding very small measured quantities of Condy's fluid (permanganate of potash); these additions are however, dependent on the data provided by the analyses.

A simple statement of the composition of the solid matter is not sufficient; it is essential that the bacteriological data should also be provided. This is especially necessary in the case of waters liable to contamination by human agencies. In tropical countries, where cholera, malaria, and other pathogenic germs are endemic, and liable through lack of sufficient care to become epidemic, the most stringent precautions are imperative. It is not to be forgotten that sterilisation of the water and the storage containers and conduits is not sufficient. Consumers frequently offend the fundamental principles of hygiene by omitting to clean the vessels in which they draw and hold water intended for home consumption.

DRINKING WATER.—In "Moore's Family Medicine and Hygiene for India" (7th Edn., by J. H. Tull Walsh, 1908, pp. 599–603) there is presented a simple statement of the dangers of drinking water indiscriminately in India and the precautions to be taken—the same remarks apply to other tropical countries. The presence of colour, usually indicative of peaty or iron compounds, can be removed by oxidation with permanganate of potash (Condy's fluid) or by filtration through charcoal, or by agitation with dry clay and subsequent

decantation. Suspended matter which causes turbidity is generally removed by filtration, but persistent turbidity or opalescence usually indicates colloidal matter; this is generally eradicated by coagulating the colloidal substance with alum. The problem of treating colloidal suspension depends on the sign of the electric charge carried by the colloid particles. Data show that in dilute solutions each colloidal particle apparently carries an electric charge either positive or negative —consequently for proper treatment the coagulating substance should have an electric charge opposite to that of the substance which contaminates the water. Mutual attraction results in the precipitation of the impurity and the added product, and the water is left pure. The presence of disssôlved inorganic or organic salts or acids is best detected in the usual manner, *i.e.* with litmus paper, and the waters classed as acid, saline, or alkaline. Acidity, which may be due to the presence of free acids, is a bad sign—such waters are capable of dissolving metals (zinc, etc.) with which they may come in contact, and are therefore harmful to the human system; neutralization may be effected by the addition of quicklime, and this will probably render such water suitable for domestic use. Inland waters containing appreciable amounts of chlorine are suspect of sewage contamination, and must be sterilised and purified with care. Natural waters containing sulphates (Epsom Salts) are generally unsuitable for drinking if present in appreciable quantities; sulphates also render water unfit for cooking purposes; it is these salts which make a water permanently hard—the best remedy is to add quicklime or use a mixture of barium carbonate and barium oxide to precipitate the objectionable sulphate. Temporary hardness is due to bicarbonate of calcium; it is removed by boiling or the addition of a little lime. Very hard water is found to be disagreeable for washing purposes; very soft water, on the other hand, although excellent does, not prove agreeable as drinking water; the best drinking water is one which is faintly alkaline and slightly hard, due to small amounts of bicarbonate of calcium. Chalybeate waters are objectionable for domestic purposes, and should be rid of their iron at their source. It is known that as a result of the development of certain otherwise harmless algæ or bacteria, and their effect on the organic compounds present, iron hydroxide in a flocculent condition has been liberated in such quantities as to choke pipes, stain walls, and so discolour the supply water as to render it objectionable for several days at a time.

The treatment of public supplies of water involves the removal of suspended and dissolved matter, both organic and inorganic. The procedure to be adopted consequently depends on the character of the water to be treated. Sand and charcoal filters, boiling, the addition

of lime, quicklime, barium compounds, or of permanganate of potash are familiar to most engineers. The intelligent use of alum and aluminium compounds makes these salts extremely valuable—probably more so than the careless addition of chlorine in the form of bleaching powder. Both these substances—alum and chlorinated lime—if added in too large quantities, give the water a disagreeable taste. The added substance should not be readily detected; if the water is unpalatable, owing to the taste of the added alum or chlorogen, etc., it is evident that far too much of the corrective has been added.

BOILER-FEED WATER.—For many reasons the water for a boiler requires to be chosen with the same care as is necessary in the case of drinking water. Bacteria do not hurt a boiler, but if their activity or destruction causes gases to be formed, "priming" will take place in the pipes. Similarly, if they result in the precipitation of sludge in the boiler, the deposit has to be removed. Gaseous waters, such as rain-water, also cause "priming" in boilers; hard waters result in precipitates being left in the boiler. Carbonate of lime (temporary hardness) produces a powdery deposit which sinks to the bottom and can be removed by "blowing off" through a proper sludge discharge valve. Sulphates of calcium and magnesium deposit a hard "scale" on the plates and tubes of a boiler; chalybeate waters are objectionable on similar grounds. Acid waters are bad; those containing chlorides of calcium and magnesium, when boiled and strongly heated, liberate hydrochloric acid, and this acid attacks the boiler plates and tubes and causes pitting by corrosion. Strong saline or alkaline water cannot be used in a boiler. Sodium chloride rapidly corrodes brass tubes and fittings and sets up electrolytic action between dissimilar metals, which may cause corrosion to a dangerous extent.

The best water for boiler-feed purposes is a clear soft water free of acidity and dissolved gases. The best test is to evaporate the sample of water and note the ebullition of gases and the amount and condition of the solid residue. Hard waters are now readily treated by special water-softening processes before being utilised in the boiler. As previously stated, temporary hardness can be removed by the addition of lime, and both temporary and permanent hardness are eradicated by using a mixture of barium carbonate and barium oxide.

WATER FOR BUILDING PURPOSES.—In the chapter on "Choice of Materials," particulars are given regarding the use of clay containing certain salts for the manufacture of bricks. It is there shown that such salts may cause a disfigurement of the appearance of the brickwork by the formation of an encrustation of salts on the exposed surface of the walls. This growth of an efflorescence may

also occur on the face of walls which are built of other porous material, *e.g.* sandstone, if the water used in the building operations is heavily charged with similar salts. The saline water will be absorbed by the porous material and the salt will be deposited on the surface from which the contained moisture is slowly evaporated. It is thought that this case resembles that of a green log which, being heated at one end, exudes sap from the other. The explanation offered is that the expansion caused by the heat enlarges the size of the pore-spaces on the sunny side of the wall and increases the capillary movement towards the cooler face, with the result that the saline water will concentrate on this side, and by subsequent evaporation produce an efflorescence on the surface of brick or stonework on the *shady* side of the wall.

The waters most liable to cause this disfigurement are those which contain soluble carbonates, sulphates and chlorides of potassium, sodium, calcium, magnesium, etc.

The most efficient method of dealing with the saline waters which contain only sulphates and carbonates is to add a mixture of barium carbonate and barium oxide. By this mean, both the temporary and permanent hardness are removed, insoluble sulphates are formed, free lime is liberated, and this helps to remove the temporary hardness due to the carbonates of calcium and magnesium. There is no simple, cheap method of removing the soluble chlorides, so that it is better to avoid using waters containing chloride salts.

Occasionally the lime of the mortar or cement contains magnesium sulphate or other soluble salts. These are dissolved in the process of building, with the result that the solution penetrates into the porous rock or brick and finally forms an efflorescence on the exposed surface of the wall. In such cases, the deposit may be removed by gently sponging the surface with very weak hydrochloric acid.

In some instances, where precautions have not been taken, the surface of good sandstone masonry becomes friable owing to the accumulation of saline matter in the interstices of the rock, with the result that ugly scaling takes place. No external application of preservative will save the facing, because the trouble is from within the masonry.

Chalybeate waters are unsuitable for building purposes where ornamental stonework is being erected or the stone facing is intended to show its natural colour. The oxidation of the iron carbonate in such waters will result in ugly red-brown stains, which it would be difficult to remove from polished surfaces, and almost impossible to wash from rough stone faces.

WATER FOR SANITARY USES.—Municipal engineers would

probably place these uses under two heads: (1) Street watering and (2) Sewage flushing. In the case of water for street watering, especially in a tropical country, it should be remembered that if there are restrictions regarding the use of the filtered supply, many people will use the unfiltered water even for cooking. Water used on roads should be of good quality. Suspended matter such as silt or colloidal matter does not necessitate filtration; the water is perfectly safe so long as it is known to be free of pathogenic germs of a dangerous character. Foul smelling water is objectionable for street watering, but it is likely that the odour can be removed by mixing dry clay with the water previous to use. Waters carrying large percentages of sulphates and chlorides may prove objectionable by the reactions which may be set up between these salts and any decaying vegetable matter lying about. Hard waters or muddy waters, if free of bacteria, are perfectly safe. All that is required of a water for street purposes is that it should be free of objectionable odours, dangerous bacteria, and not liable to cause chemical action of a disagreeable, injurious, or unhealthy nature with any organic or metallic substances with which it may come in contact.

Water that is to be used solely for flushing should not be dissimilar to that used for street watering. However, much greater latitude is permitted in the quality of water not intended for use above ground. Some constituents in an impure water may be very useful as dilutents in sewage, owing to the possibility of their effecting desirable interactions; thus, a strongly chalybeate water may render the sewage odourless as a result of the iron in the former combining with the sulphuretted hydrogen of the latter to precipitate mutually sulphide of iron.

FORMS OF ANALYSES.—In "Emergency Water Supplies" (A. Beeby Thompson, 1924, pp. 161–76) several pages are devoted to the question of testing the quality of water for domestic purposes. The TYPE form of ANALYSIS recommended is shown below, although the writer says:

"No chemist at any time would be likely to give all the particulars enumerated below.

Characters observed	Results
Appearance	Clear and bright
Colour	None
Odour in the cold	None
Odour at 65°C (150°F) ..	Slight, not identifiable
Reaction	Faintly alkaline
Sediment	Small—inorganic

Substances estimated	Grains per gallon	Parts per million
Free or saline ammonia	0.003	0.04
Albuminoid ammonia	0.004	0.05
Oxygen absorbed in 15 minutes at 80°F	–	–
Oxygen absorbed in 4 hours at 80°F ..	0.210	3.00
Chlorine	3.0	43
Nitrates (nitric acid as)	1.0	14
Nitrates (nitrous acid as)	–	–
Nitrogen (in nitrates and nitrites) ..	0.2	3
Total hardness (soap test)	20	285
Temporary hardness	16	229
Permanent hardness	4	57
Total solid residue	30	430

Then is added the composition of the solid residue, per cent.

Metals.—Iron (Fe), aluminium (Al), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K).

Acids.—Carbonic (CO_3), sulphuric (SO_4), hydrochloric (Cl), nitric (NO_3), silicic (SiO_3).

The writer, however, goes on to say that :

" The composition will then be shown as silica, alumina, and ferric oxide not united with acids as too uncertain ; then calcium carbonate, sulphate and chloride; sodium carbonate, sulphate, chloride, or nitrate ; and potassium chloride, organic matter and loss, *according to the opinion of the chemist as to the compounds preferentially formed and the supply of constituents for them.*" (The italics are mine.)

With regard to the tabulated statement there is little to be said except that it is admittedly elaborate.

Water analysis may be stated in several ways, three of which are given on the following page.

" So far as appearance goes, these statements might represent three different waters ; and yet the analytic data are the same." (F. W. Clarke.)

Although the first two methods of stating results are in common use, the procedure is not free from unjustifiable assumptions. For several years an effort has been made to standardise water analyses to the form shown in III, *i.e.* in terms of the percentages of acid and basic radicles or ions. In this method only occasional conventions are introduced, *e.g.* silica is taken as colloidal silica not as the silicic ion.

I		II		III	
Grains per Imp. gal.		Parts per million		Per cent.	
SiO_2 ..	0.891	$CaSO_4$ ..	457.7	SiO_2 ..	1.26
SO_3	32.601	$MgSO_4$ ..	236.0	SO_4	55.28
CO_2	4.554	K_2SO_4 ..	9.4	CO_3	8.78
Cl	2.681	Na_2SO_4 ..	62.5	Cl	3.79
Na_2O ..	11.463	NaCl	63.2	Na	12.02
K_2O	0.355	Na_2CO_3 ..	156.9	K	0.41
CaO	13.117	Na_2SiO_3 ..	21.9	Ca	13.24
MgO ..	5.530	$(FeAl)_2O_3$ ..	2.7	Mg	4.69
$(FeAl)_2O_3$ ..	0.189	Mn_2O_3 ..	2.7	R_2O_3	0.53
Mn_2O_3 ..	0.189	Ignition ..	34.2		
Ignition ..	2.397	Excess SiO_2	1.3		100.00
	73.967		1048.5	" Ignition " omitted. Salinity, 1,014 parts of anhydrous, inorganic, solid matter, per million of water.	
Less O = Cl	0.604				
	73.363				

The analyses are by W. P. Headden of a sample of water from the Platte River near Greeley in Colorado.

CLASSIFICATION OF WATERS.—According to Chase Palmer (see "The Geochemical Interpretation of Water Analyses," *Bull. U.S. Geol. Surv.*, No. 479, 1911):

"Two fundamental properties are recognised—namely, *AKLALINITY* and *SALINITY* which are subdivided into groups. Salinity is measured by the sum of the 'strong-acid' radicles, SO_4, Cl and NO_3, which balance an equivalent number of basic radicles. If the basic radicles are partly or wholly alkaline, that is, Na or K, their proportion of salinity is said to be *primary*. The remaining salinity, due to the radicles Ca, Mg and Fe, is called *secondary*. If, however, the acid radicles are in excess of the basic, *tertiary* salinity or acidity appears, and hydrogen ions must be taken into account. When the alkaline radicles exceed those of the strong acids, their excess is the measure of *primary* alkalinity, which represents hydrolyzed carbonates or bicarbonates. The 'weak-acid' radicles CO_3 and HCO_3 which balance any excess of the alkaline earths over the stronger acids, produce *secondary* alkalinity."

Upon these properties Palmer

"has developed a classification of natural waters, which correlates them with their geologic origin. Waters issuing from areas of crystalline, feldspathic rocks, are characterized by high primary alkalinity, low concentration, and a notable proportion of silica. Waters from sedimentary regions, especially where limestone is abundant, show secondary alkalinity. Ocean water and other similar

brines are almost entirely saline, and alkalinity is nearly or even wholly wanting in them." (See F. W. Clarke, "The Data of Geochemistry," *Bull. U.S. Geol. Survey*, No. 616, 1916, p. 63.)

F. W. Clarke, after an elaborate presentation of details, tabulates the various types of natural waters, which include lakes and rivers, enclosed basins and the sea, and mineral wells and springs, in the following order :

I. *Chloride waters*, whose principal negative ion is chlorine.
  A with sodium as principal positive ion.
  B with calcium as principal positive ion.
  C waters rich in magnesium.
II. *Sulphate waters*, with SO_4 as principal negative ion.
  A with sodium as principal positive ion.
  B with calcium as principal positive ion.
  C with magnesium as principal positive ion.
  D waters rich in iron or aluminium.
  E waters containing heavy metals such as zinc.
III. *Sulphato-chloride waters*, with SO_4 and Cl both abundant.
IV. *Carbonate waters*, with CO_3 or HCO_3 as principal negative ion.
  A with sodium as principal positive ion.
  B with calcium as principal positive ion.
  C chalybeate waters.
V. *Sulphato-carbonate waters*. SO_4 and CO_3 both abundant.
VI. *Chloro-carbonate waters*. Cl and CO_3 both abundant.
VII. *Triple waters*, containing chlorides, sulphates and carbonates in equally notable quantities.
VIII. *Siliceous waters*, rich in SiO_2.
IX. *Borate water*. Principal negative radicle B_4O_7.
X. *Nitrate waters*. Principal negative ion NO_3.
XI. *Phosphate waters*. Principal negative ion PO_4.
XII. *Acid waters*, contain free acids.
  A Acid chiefly sulphuric.
  B Acid chiefly hydrochloric.

METHODS OF TESTING WATER.—The subject of the quality of water is so important that perhaps it may be to the mutual benefit of the civil engineer and the geologist if the methods of testing are briefly discussed.

The simple property of hardness often has far-reaching consequences. It is to be remembered that one part of calcium carbonate in 100,000 parts of water necessitates the use of 8 parts of soap before a lather is obtained. It is estimated that the citizens of Glasgow spend £40,000 less annually on soap since the soft water from Loch Katrine was brought to their city.

Occasionally an impure water becomes gradually purified by peculiar circumstances and vice versa, but without actual testing these facts might not be suspected. For example, the Schuylkill river above

Philadelphia is heavily charged with iron salts and acids—the result of contamination by mine drainage. Lower down, the stream flows over limestone rocks and, as a result of the interaction between the acids in the water and the limestone of the river bed, there is neutralisation. Its acid character disappears, lime and iron are precipitated, and what was water unfit for use is found to be soft and wholesome.

The worst kinds are waters carrying appreciable amounts of bacteria—perhaps just too large for safe use. This cannot be ascertained without careful bacteriological examination. For this reason great credit is due to the chemist, Vant Hoff. He observed that bacteria tend to settle when the velocity of a current of water (in which they occur) is reduced. By this fact he enabled the town of Rotterdam to obtain its water-supply from the tidal Maas (Rhine) on which it is situated. At flood tide the river water is at its greatest dilution and lowest velocity, and the bacteria content is reduced 50 per cent.; it is at this time that the supply for the town is withdrawn from the river.

Although it is impossible to expect an engineer or a field geologist to make a complete analysis of a sample of water, he may, with advantage, carry out a few simple tests, and speak in precise terms when discussing the quality, etc., of a given water. Such terms as turbidity, odour, colour, acidity, alkalinity, hardness, etc. often have a quantitative meaning.

(1) *Turbidity.*—The turbidity of a water may be expressed by the depth at which a platinum wire of 1 mm. (0.04 inch diameter) is visible. Thus a turbidity of 0.1 means that the wire can be seen at a depth of 10 inches. A turbidity of 1 indicates that the wire is lost sight of at a greater depth than 1 inch. Turbidity is frequently due to the presence of colloidal substances; these colloids are capable of removal by means of exceedingly weak acid or alkaline solutions.

(2) *Colour.*—This can be estimated by comparing waters with dilute solutions of salts of platinum and cobalt. If the ratio of cobalt to platinum is varied, it is possible to simulate very closely the hue of the natural water; the colour is recorded in terms of the platinum—one part of this metal in 10,000 parts of water equals one unit of colour.

(3) *Odour.*—This is best tested by warming the water to 65° C. in a closed vessel and then lifting the lid for scrutiny. Odour is said to be due to the growth of certain odour-producing algæ and diatoms which develop best in shallow waters exposed to the sunlight. Hence the water of covered or deep reservoirs is less liable to this objectionable character. The "fishy" odour of cod liver oil is ascribed to the protozoa *Uroglena*, while that of ripe cucumbers is said to be due

to *Synura*. Grassy odours are traceable to the blue-green algæ *Anaboena* (one of the Cyanophycæ). Vegetable odours indicate the presence of the diatoms *Synedra* or *Melosira*. Aromatic odours (geranium, etc.) are generally caused by the existence of the diatom *Asterionella*.

(4) *Alkalinity.*—This is due to the presence of dissolved carbonates of the alkaline earth metals; such waters impart a slight blue tinge to neutral litmus paper; they also change the colour of methyl orange to a distinct canary-yellow tint. The method of determining the amount of carbonate consists in taking 200 cc. of the water in a white porcelain basin, adding two drops of a concentrated solution of methyl orange, and titrating with a one-fifth normal solution of hydrochloric acid, until the canary-yellow colour of the water is changed to a faint pink. About 20 cc. of the acid are usually required to neutralise 0.40 grams of sodium carbonate, so that if only 3.70 cc. have been added to the basin it means that 200 cc. of water contain 0.074 grams of sodium carbonate, *i.e.* 370 grams per million parts of water.

(5) *Acidity.*—This may be due to organic acids as in the case of peaty waters. The best indicator is an alcoholic solution of phenolphthalein; this is added to 200 cc. of the water to be tested in a white porcelain basin and titrated with a standard (one-fifth normal) alkali (sodium carbonate) solution until a purple red colour is attained. The amount of one-fifth normal alkali solution added indicates the amount of alkali necessary to effect neutralisation of the acid in the water; this is an index of the amount of the acid present.

(6) *Solids.*—This includes both the suspended and dissolved matter in the water. Filtration will possibly remove most of the suspended matter, and this can be estimated by igniting and weighing the filter paper ash. The dissolved salts are ascertained by evaporating filtered water in a basin until a dry residue is obtained. In each case the quantity of water taken must be known, so that the proportion of solids per 100,000 parts of water can be calculated; the dissolved solids give the degree of hardness of the water.

(7) *Hardness.*—Hardness is measured in degrees by the English, French, or German scale. The French degree of hardness represents the grams of calcium carbonate in 100,000 parts of water (100 litres). The German degree of hardness is the number of grams of calcium oxide in 100 litres. The English or Clark degree is the number of grains in one Imperial gallon of water (*i.e.* parts per 70,000). In determining the alkalinity we also ascertain the temporary hardness. It has already been stated that the hardness of water may be *temporary*, due to bicarbonates of calcium and magnesium which can be pre-

cipitated by boiling, and *permanent*, due to the sulphates of calcium and magnesium. The degree of permanent hardness can either be ascertained separately or found by subtracting the temporary hardness from the total hardness. The tendency nowadays is to express hardness and alkalinity in parts per million.

Detailed explanations regarding the above chemical tests and particulars of the chemistry of softening waters are given in that very useful book, "Fuel, Water and Gas Analysis," by J. B. C. Kershaw (1907).

(8) *Iron.*—A large percentage of iron is readily detected by the taste of the water. It can, however, be estimated by oxidising and precipitating the iron (ferrous salts) by adding an acidified solution of potassium permanganate. The decolourisation of the potassium permanganate should be effected in 15 minutes; if the permanganate becomes decolourised after a number of hours it is likely organic substances are present.

(9) *Organic Matter.*—This is probably the most dangerous constituent in waters and its determination is of prime importance. If continued absorption of oxygen has been observed, the necessity for prolonged treatment with acidified potassium permanganate serves as an indication of the presence of organic compounds. The dry residue obtained by evaporating water may contain the organic substance, and this can be ascertained by igniting the residue and noting the loss in weight. Organic matter may be of animal or vegetable origin. As was noticed above, algæ and diatoms may be present. Pathogenic bacteria are likely to occur in poisonous amounts, and these should be carefully looked for by a thorough bacteriological examination (see "Public Water Supplies," by F. E. Turneaure and H. L. Russell (1906), p. 123).

(10) *Pollution.*—Perhaps the simplest way of detecting pollution is to add a characteristic chemical to the source from which pollution is suspected, and then look for traces of the chemical at the point where the water is to be drawn. The substance *saprol* can be detected by its penetrtaing odour when present in the proportion of one part in a million parts of water; by taste (naphtha-like) it can be recognised when present as 1 part in 2 million. The most powerful substance for this purpose is fluorescein. Fluorescien, dissolved in alcohol and diluted with 5 per cent. of ammonia solution, can be detected when present in the proportion of 1 part in 2,000,000,000 parts of water by means of the fluoroscope. This is a white glass tube half an inch in diameter and from 3 to 4 feet long; it is closed at one end by a rubber cork. In such a tube normal water has a sombre blue colour which changes to a clear green if fluorescein is present.

Common Names of Chemicals.

Common Names.	Chemical Names and Formulæ.
Alum	Sulphate of Aluminium and of Potassium, etc.
Aqua Fortis	Nitric Acid, HNO_3
Aqua Regia	Nitro-Hydrochloric Acid
Calomel	Mercurous Chloride, Hg_2Cl_2
Carbolic Acid	Phenol C_6H_5OH
Caustic Potash	Potassium Hydrate KOH
Caustic Soda	Sodium Hydrate, NaOH
Chalk	Calcium Carbonate, $CaCO_3$
Copperas	Sulphate of Iron
Corrosive Sublimate	Mercuric Chloride, $HgCl_2$
Cream of Tartar	Potassium Bitartrate
Epsom Salts	Magnesium Sulphate
Ether	Diethyl Oxide $(C_2H_5)_2O$
Fire Damp	Light Carburetted Hydrogen
Galena	Lead Sulphide, PbS
Glauber's Salt	Sodium Sulphate
Glucose or Grape Sugar	Dextrose $C_6H_{12}O_6$
Goulard Water	Basic Acetate of Lead
Iron Pyrites	Iron Di-Sulphide, FeS_2
Jewellers' Putty	Oxide of Tin
Laughing Gas	Nitrous Oxide, N_2O
Lime	Calcium Oxide, CaO
Lunar Caustic	Silver Nitrate, $AgNO_3$
Mosaic Gold	Bi-Sulphide of Tin
Muriatic Acid	Hydrochloric Acid, HCl
Olefiant Gas	Ethylene, C_2H_4
Plaster of Paris	Calcium Sulphate $CaSO_4H_2O$
Quartz	Silicon Dioxide, SiO_2
Realgar	Arsenic Di-Sulphide, As_2S_2
Red Lead	Oxide of Lead, Pb_3O_4
Rochelle Salt	Sodium Potassium Tartrate
Rouge	Ferric Oxide, Fe_2O_3
Salammoniac	Ammonium Chloride
Salt, Common	Sodium Chloride NaCl
Salt of Tartar	Potassium Carbonate
Saltpetre	Potassium Nitrate, KNO_3
Salts of Lemon	Potassium Quadroxulate
Slaked Lime	Calcium Hydrate
Soda	Sodium Carbonate
Spelter	Zinc Zn.
Spirits of Hartshorn	Amm. Hydroxide, NH_4OH
Spirits of Salt	Hydrochloric Acid, HCl
Sugar of Lead	Lead Acetate
Tartar Emetic	Potass. Antimony Tartrate
Verdigris	Basic Copper Acetate
Vermilion	Sulphide of Mercury HgS
Vinegar	Dilute Acetic Acid
Vitriol, Blue	Copper Sulphate
,, Green	Ferrous Sulphate
,, Oil of	Sulphuric Acid H_2SO_4
,, White	Zinc Sulphate
Volatile Alkali	Ammonia NH_3

(*Science Year Book.*)

SUBJECT INDEX

THE LONDON AND NORWICH PRESS, LIMITED, ST. GILES WORKS, NORWICH